# Development of Post Occupancy Evaluation Method for Climate Adaptive Building Shells: In Case of User Satisfaction Assessment of CABS

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Approval of the Institute of Graduate Studies and Research

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I certify that this thesis satisfies all the requirements as a thesis for the degree of Doctor of Philosophy of Architecture.

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We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Doctor of Philosophy of Architecture.

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# ABSTRACT

Building development is one of the human activities with the greatest impact on sustainability. Many alternatives to address sustainability in architecture have been proposed in recent years and Climate Adaptive Building Shell (CABS) are one of the most promising solutions to date. CABS provide a response to this problem due to their adaptability and modifiability. Although CABS are promising solution for reducing energy consumption of the building, they have reputation for decreasing the occupant’s satisfaction. The examination of the CABS literature review using PRISMA methodology reveals that most of the research attention in this subject has been focused on economic and technological factors, while the occupant-centric study has been neglected. As a result, the fundamental purpose of this thesis is to conduct an occupant-centric study.

The CABS literature and database were investigated in the first phase of this thesis. As a result, CABS office buildings were evaluated based on user-facade interaction types and scenarios to achieve the study's occupant-centric purpose. Finally, a new taxonomy for CABS office buildings that covers a wide range of topics was introduced. In the other hand, the literature review highlights the lack of research on occupants’ satisfaction, productivity and needs for this system. POE has traditionally been an effective approach for assessing user satisfaction. However, in its current state, this technique cannot fulfill the CABS's complexity and multi-domain properties. Thus, in second phase of study, after analyzing POE in general and identifying comfort characteristics, an attempt was made to design a unique POE model that can fulfill CABS requirements.

As a result, a dynamic cloud-based POE was created within three main stages. In the first stage the model has been conceptualized with help of Human-Computer Interaction and Internet of Things Principles. The occupant-centered model tries to pinpoint the precise moment of discomfort. In the second stage, application of the model has been studied. For the Machine Learning of the model an active surrogate model with Artificial Neural Network architecture method has been applied. Lastly the relational data management system of the model has been studied. In last step the implementation of the model has been discussed. Finally, data assessment approaches for multi-criteria analysis and decision-making for CABS has been presented. The proposed model fills a gap in the literature of CABS studies linked to POE; nevertheless, due to a lack of recorded case studies on CABS, creating practical research on CABS for POE using proposed model is required.

**Keywords:** CABS, POE, User-Centric Design, Dynamic-Cloud modelling, HCI, ML

# ÖZ

Bina geliştirme, sürdürülebilirlik üzerinde en büyük etkiye sahip insan faaliyetlerinden biridir. Son yıllarda mimaride sürdürülebilirliği ele almak için birçok alternatif önerilmiştir ve iklim uyumlu bina kabuğu (CABS) bugüne kadarki en umut verici çözümlerden biridir. CABS, uyarlanabilirlikleri ve değiştirilebilirlikleri nedeniyle bu soruna bir yanıt sağlar. Her ne kadar CABS, binanın enerji tüketimini azaltmak için umut verici bir çözüm olsa da, bina kullanıcılarının memnuniyetini azaltma konusunda itibara sahiptir. CABS literatür taramasının PRISMA metodolojisi kullanılarak incelenmesi, bu konudaki araştırmaların çoğunun ekonomik ve teknolojik faktörlere odaklandığını, ancak kullanıcı merkezli çalışmanın ihmal edildiğini ortaya koymaktadır. Sonuç olarak, bu tezin temel amacı, kullanıcı merkezli bir çalışma yapmaktır.

Bu araştırmanın ilk aşamasında CABS literatürü ve veri tabanı incelenmiştir. Sonuç olarak, CABS ofis binaları, çalışmanın kullanıcı merkezli amacına ulaşmak için kullanıcı-cephe etkileşim türleri ve senaryoları bazında değerlendirilmiştir. Son olarak, CABS ofis binaları için çok çeşitli konuları kapsayan yeni bir sınıflandırma tanıtılmıştır. Öte yandan, literatür taraması, bu sistem için bina kullanıcılarının memnuniyeti, üretkenliği ve ihtiyaçları konusunda araştırma eksikliğini vurgulamaktadır. Kullanım Sonrası Değerlendirme, geleneksel olarak kullanıcı memnuniyetini değerlendirmek için etkili bir yaklaşım olmuştur. Ancak, mevcut durumunda bu yaklaşım, CABS'nin karmaşıklığını ve çok alanlı özelliklerini yerine getiremez. Böylece çalışmanın ikinci aşamasında, genel olarak POE'nin analizi ve konfor özelliklerinin belirlenmesinden sonra, CABS gereksinimlerini karşılayabilecek benzersiz bir POE modeli tasarlanmaya çalışılmıştır.

Sonuç olarak, üç ana aşamada dinamik bir bulut tabanlı POE oluşturuldu. İlk aşamada model, İnsan-Bilgisayar Etkileşimi ve Nesnelerin İnterneti İlkeleri yardımıyla kavramsallaştırılmıştır. Kullanıcı merkezli model, tam olarak rahatsızlık anını belirlemeye çalışmıştır. İkinci aşamada ise modelin uygulaması incelenmiştir. Modelin yapay öğrenmesi için Yapay Sinir Ağı mimarisi yöntemi ile aktif bir vekil model uygulanmıştır. Son olarak modelin ilişkisel veri yönetim sistemi incelenmiştir. Son aşamada ise modelin uygulanması tartışılmıştır. Son olarak, CABS için çok kriterli analiz ve karar verme için veri değerlendirme yaklaşımları sunulmuştur. Önerilen model, POE ile bağlantılı CABS çalışmaları literatüründeki bir boşluğu doldurmaktadır; yine de, CABS üzerine kaydedilmiş vaka çalışmalarının olmaması nedeniyle, önerilen modeli kullanarak POE için CABS üzerine pratik araştırmaların oluşturulması gerekmektedir.

**Anahtar Kelimeler**: CABS, POE, Kullanıcı Merkezli Tasarım, Dinamik Bulut modelleme, HCI, ML

# DEDICATION

To all my loved ones who supported me during all ups and downs of this journey

# ACKNOWLEDGMENT

First and foremost, I would like to express my utmost appreciation and gratitude to my supervisor Prof.Dr. Sadiye Müjdem Vural that showed me the path to success with all her knowledge, patience, and love. Since the start of writing this thesis, the world has been experiencing one of the most challenging periods in its history. As a PhD student and young researcher during the pandemic, it wouldn’t be possible for me to battle all obstacles if not for my supervisor, who stood by me and encouraged me to follow my dream till the end. She has been more than just a supervisor during the last years; she became a friend and a role model, and I will cherish this friendship forever. Her helps and supports are beyond words, and I will never forget all her efforts.

In addition, I would like to extend my appreciation to the monitoring jury members, Assoc. Prof. Dr. Gökçe Tuna Taygun and Assoc. Prof. Dr. Polat Hançer for their contribution to the development process of the thesis in past years. Without a doubt, their invaluable guidance improved the thesis massively.

I thank all the PhD defense jury members, specially Prof. Dr. Leyla Tanaçan and Prof. Dr. Aslıhan Ünlü for taking time out of their busy schedules and participating in this defense. Presenting the study to them and receiving their invaluable feedback has been an honourable experience.

Last but not least, I would like to thank my family, my parents and my younger brother, who has always believed in me. They patiently stood by my side during this journey's ups and downs. Without their constant love and support throughout my life, I wouldn’t be standing where I am today, and I cannot thank them enough. Additionally, I would like to thank my partner, Panayotis Yannakas, who helped me enormously in my academic and personal life. He has been my rock in the last few years and pushed me to dream big as he believed I could achieve what I dream for. And for sure, I would like to thank all my friends and colleagues in the Department of Architecture, EMU. They have been true friends to me over the last years, and all their help, support, and memories will stay with me forever.

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| | |
|---|---|
| AF | Adaptive Façade |
| AI | Artificial Intelligent |
| ANSI | American National Standards Institute |
| ASHRAE | American Society of Heating, Refrigerating and Air-conditioning Engineers |
| BMS | Building Management System |
| CABS | Climate Adaptive Building Shell |
| EPA | Environmental Protection Agency |
| HCI | Human-Computer Interface |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IAQ | Indoor Air Quality |
| IEQ | Indoor Environment Quality |
| IES | Illuminating Engineering Society |
| IoT | Internet of Things |
| LEED | Leadership in Energy & Environmental Design |
| LRC | Lighting Research Center |
| ML | Machine Learning |
| MPV | Predicted Mean Vote |
| OCAFAS | Occupant-Centered Adaptive Façades Assessment Survey |
| POE | Post-Occupancy Evaluation |
| PPD | Predicted Percentage Dissatisfied |
| PRISMA | Preferred Reporting Items for Systematic Reviews and Meta-Analyses |

| | |
|---|---|
| RH | Relative Humidity |
| SAW | Simple Additive Weight |
| SET | Standard Effect Temperature |
| SPSS | Statistical Package for the Social Sciences |
| UI | User Interface |
| VOC | Volatile Organic Compound |
| WHO | World Health Organization |

# Chapter 1

# INTRODUCTION

Architecture is one of the critical fields of study that may portray many elements of human existence throughout histories, such as culture, climatic changes, resources, and many other qualities. As a result, architecture might be described as "journalism in stone." Going through various periods of history may emphasise the significance of a range of concerns owing to the demands of individuals, society, and the environment at various times. A review of architectural developments over the previous decade reveals that sustainable development is the primary concern of this period. The footprints of this issue may be seen in architecture since the 1970s, but especially after 1973 and the global energy crisis, the label of sustainable development received more attention (Bennetts et al., 2003).

The quantity of energy consumed by buildings was the catalyst for the subject of sustainable development to emerge in architecture. Among all human activities, the construction industry accounts for about half of all energy use (Figure 1). As a result, one of the primary aims became the creation of methodologies and approaches to assist buildings in having less negative environmental, economic, and social impacts. In 1987, the World Commission on Environment and Development offered a comprehensive definition of sustainable development (Minke, 2012), which is quoted as follows:

> Humanity has the ability to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of future

generations to meet their own needs… sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as present needs" (Sev,2009).

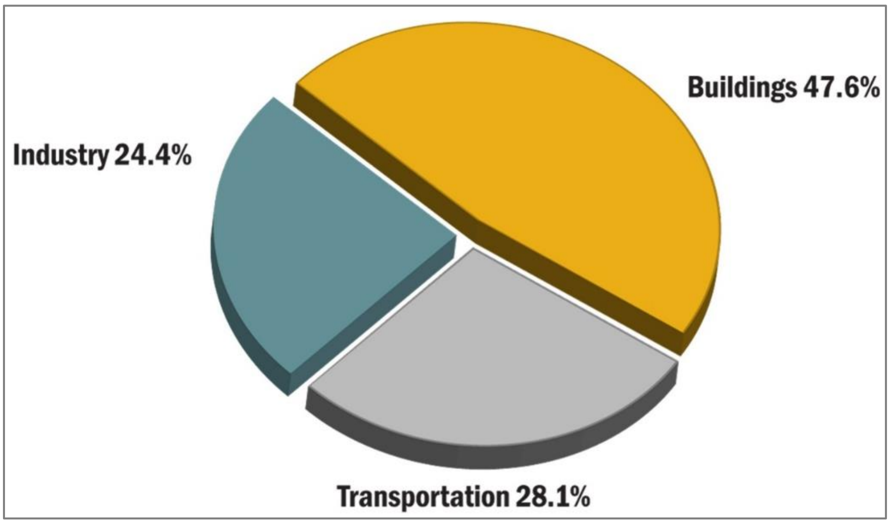


Figure 1: Energy Consumption of Sectors (Pérez-Lombard et al., 2008)

Discussions on this new trend in architecture remained mainly theoretical until 1990s. However, after the Earth Summit in Rio de Janeiro in 1992, essential elements for architectural practice were introduced for accomplishing this aim. This meeting aimed to provide a framework for countries to grow themselves socially, economically, and ecologically. This summit focused on eight major themes, including land use planning, innovative building, resource development, energy efficiency, and so on (Summit, 1992).

From this moment on, various alternatives were offered to architecture, which they primarily classified into two groups: active and passive techniques. The first strategy seeks to improve the degree of sustainability in the built environment via new technological devices (Guy and Farmer, 2001, Roaf. et al., 2009). These systems are used for decentralized energy production and delivery from renewable resources, which increases efficiency levels. Passive buildings, and from the other hand, are those in which the design and shape of the building itself, including its infrastructure, play significant roles in receiving and transferring renewable sources to reduce energy demand for lighting, heating, and cooling (Sadineni, et, al., 2011).

Aside from the energy conservation goal, the building sector also faces a growing requirement to create environments as healthy, productive, and pleasurable as possible while being cost-effective. Given these continuous advancements, whether the active or passive approach can achieve these holistic aims (EU. Directive, 2010).

New technologies, materials, and design concepts must be constantly developed to get near to this goal. Such advancements can boost energy efficiency while also improving the quality of the interior environment, which improves occupant comfort. Building shells play an essential part in this process (Perino and Serra, 2015). Building shells are placed at the boundary between the interior and outside environments. They are thus subject to various changeable factors such as changes in meteorological conditions (daily, seasonally, and annually) or occupant demands based on their needs and comfort. Traditional building shells often have static qualities and lack the capacity to respond to these difficulties. With the assistance of contemporary computer science and technology improvements, changing to climate adaptable building shells (CABS) with adaptability characteristics provides potential to improve the energy consumption of the building while satisfying the demands of the occupants (Addington, 2009).

CABS can enhance sustainable energy sources use while improving building comfort conditions. CABS can respond to climatic variations on an hourly, daily, seasonal, and annual basis. The term “adaptive” refers to the ability to respond to or benefit from outside climate circumstances to meet efficiency and, more importantly, to effectively meet the comfort and well-being of the occupants (Meijer, 2011, Annunziata et al., 2013).

Various current projects with adapted building shells are being built all over the world. As of 2018, there are 165 examples of buildings with adaptive shells based on the CABS database developed by COST Action TU 1403 adaptive facade network, supported by COST (European Cooperation in Science and Technology), which is constantly updated. However, specific information on these envelopes’ performance, design, and construction are not widely available (Aelenei et al., 2018).

There are several shell solutions commercially available on the market now. It is still unclear how they should be established, run, managed, and assessed. It is feasible to analyze and appreciate how CABS were constructed and taken into account during the seven main project delivery stages described below:

1. Predesign and design process,
2. Schematic and conceptual design,
3. Design development and construction,
4. Design assist (pre-construction testing),
5. Commissioning,
6. Occupant operation (behaviour),
7. Post-occupancy evaluation and monitoring.

The study of the CABS based on the above phases demonstrates the benefits and obstacles encountered in specific solutions in terms of energy usage, comfort, operation, and maintenance. To date, there is limited investigation on CABS on the aforementioned phases in the literature, and there are just a few case studies that have been reported (Karanouh and Kerber, 2015, Attia, 2018).

Understanding the importance of studying the mentioned seven stages, particularly occupant-centric research on CABS, became the primary goal of this thesis. The findings and analysis of the CABS literature –detailed in great depth in the coming sections – underscore the necessity for a Post-occupancy Evaluation (POE) study on this system. In addition to examining the literature and the most recent CABS database, this PhD thesis emphasises the need for occupant-centric studies in this field. In this regard, after reviewing POE in general, it creates a POE model capable of competing with CABS' complexity and multi-domain properties. Based on occupant-centric principles, the suggested approach strives for real-time data collection and evaluation to provide a realistic picture of occupant satisfaction, productivity, and perception of CABS. Finally, a multi-criteria analysis using a simple additive weight approach is provided, which aids in future design decision-making based on occupant feelings.

## 1.1 Problem Statement

As previously stated, it is important to do more research and evaluation from different perspectives in order to understand this new technology. In the other hand, research in this field is gaining momentum which indicates the importance of the study over all phases in this subject. This study attempted to focus on POE for CABS to fill one of the system's literature gaps. As the building sector continues to develop and construct automated, energy-efficient shells, it is critical for researchers and architects to consider optimising the total work, living, and learning experience of users. POE has traditionally been used to analyse and evaluate user experiences (Loonen et al., 2013).

POE research are required for CABS because there is a growing desire to satisfy more demanding environmental, social, and economic performance targets. The implementation of the CABS, on the other hand, required a specific method to obtain feedback on the users' satisfaction and building performance utilizing the POE approach. The POE for CABS includes researching occupant interactions with the shells and overall building performance regarding energy efficiency, indoor environmental quality (IEQ), occupant satisfaction, well-being, and productivity (Attia and Bashandy, 2016). According to the literature study, there is a lack of complete POE for CABS that includes qualitative and quantitative assessment and, more crucially, incorporates users (Attia et al., 2015, Attia et al., 2018).

The conducted systematic investigation provides substantial proof for what has been said concerning the discovered gap in the literature. In this way, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) research has been conducted to support the validity of the knowledge gap. Several papers were discovered throughout the literature research that indicated the importance of investigating CABS after it has been occupied. The primary goal of architecture is to provide a safe place for humans and provide a satisfying experience; however, in this study field, the emphasis has been on energy use and assessment. To summarise, the findings of the PRISMA research suggests that investigating POE for CABS has been ignored. Most studies have focused on energy concerns; furthermore, several academics in recent publications have acknowledged the importance of working on POE for CABS and conducting case studies.

Publications from online sources, all in English (Scopus, Web of Science, Google Scholar and Research Gate) between 2010 and 2021, were discovered for this

PRISMA study. In all, 103 papers were screened, with 12 articles being eligible for further examination. The final result demonstrates no quantitative research on this topic, and only four articles incorporated any qualitative synthesis. Following Figure 2 illustrates the summary of the PRISMA.

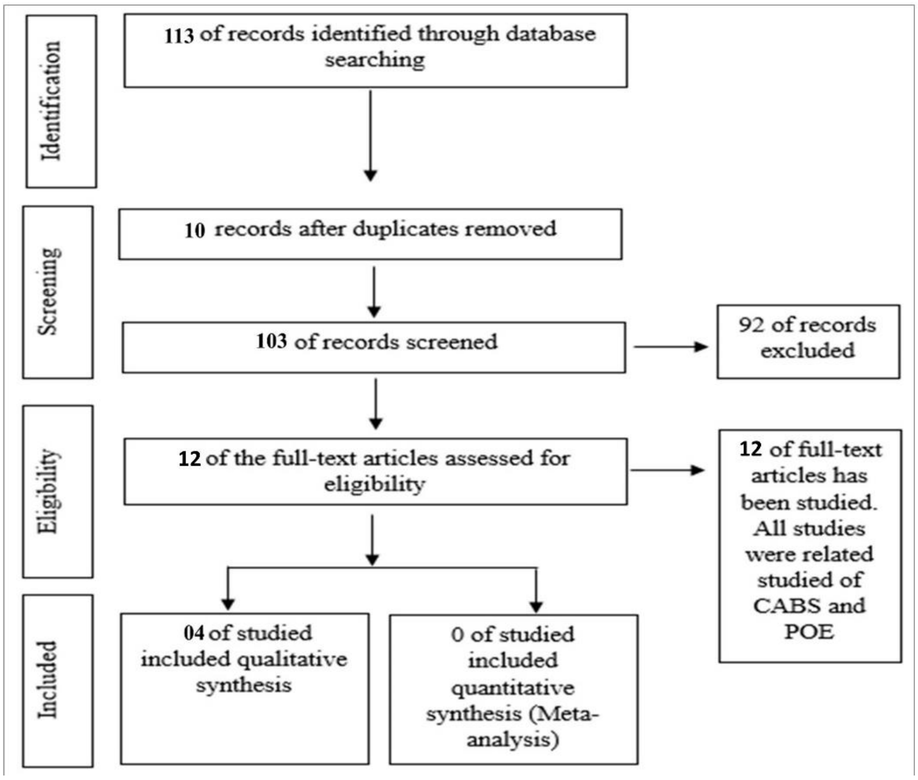


Figure 2: Summary of PRISMA Study (Author, 2021)

Table 1 below presents all of the details of the PRISMA study to emphasise the literature gap.

Table 1: PRISMA analysis (Author, 2021)

| | | |
|---|---|---|
| Identification | Records identified through database Researching<br>NUMBER: 113 | |
| | Number of duplications: 10<br>**Records after duplications removed: 103** | |
| Screening | **Records screening 103** | |
| | Title of publication | Focus |

| | | |
|---|---|---|
| | A biomimetic approach for the multi-objective optimisation of kinetic façade design | Energy |
| | A classification approach for adaptive facade | Theory |
| | A comparative study of the energetic performance of climate adaptive building façade compared to static façade design in Mediterranean climate | Energy |
| | A model for performance evaluation of climate adaptive building envelopes using parametric models and multi-criteria optimisation | Energy |
| | A novel methodology to optimise energy performance for transparent adaptive facades | Energy |
| | A study on the impact of climate adaptive building shells on indoor comfort | Energy |
| | Active building envelope systems toward renewable and sustainable energy | Theory |
| | Adaptive building shells | Theory |
| | Adaptive building and skin: an innovative computational workflow to design energy efficient building in different climate zones | Energy |
| | Adaptive building façade optimisation: an integrated green-IBM approach | Energy |
| | Adaptive biomimetic façade: enhancing energy efficiency of highly glazed buildings | Energy |
| | Adaptive façade design for the regulation of visual comfort | Energy |
| | Adaptive façade system-review of performance requirements, design approaches, use cases and market needs | Energy/ Theory |
| | Adaptive facades in temperate climate. An in-use assessment of an office building | Assessment/ Users |
| | Adaptive façade system assessment" an initial review | Assessment |
| | Adaptive system development for secondary skin | Theory |
| | Advanced building envelopes: design and construction methods | Theory |
| | An integrated design process of climate adaptive building shells using generative algorithm | Theory |
| | Assessing the performance of an advanced integrated façade by means of simulation: the ACTRESS façade case study | Assessment |
| | Assessing the performance potential of climate adaptive greenhouse shells | Assessment |
| | Assisting the development of innovative responsive façade elements using building performance simulation | Assessment |
| | Automated adaptive façade functions in practice-case on office buildings | Theory |
| | Climate responsive technologies for thermal renovation of opaque façade | Theory |

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| | Building performance simulation of adaptive facades | Energy |
| | Challenges and future directions of smart sensing and control technology for adaptive façade monitoring | Theory |
| | Climate adaptive building shells for office buildings in Egypt: a parametric and algorithmic daylight tool | Energy |
| | Climate adaptive building shells for plus-energy-buildings, designed on bionic principles | Energy |
| | Climate adaptive building shells. Development of building shells with variable, climate-controlled properties, climate adaptive building shells | Theory |
| | Climate adaptive building shells for the future optimisation with an inverse modelling approach | Energy |
| | Climate adaptive building shells: state of the are and future challenges | Theory |
| | Climate adaptive building solutions based on the autonomous movement of wooden bi-layered structures | Theory |
| | Climate adaptive building skins for tropical climates: a review center on the context of Colombia | Theory |
| | Climate adaptive buildings: systems and materials | Theory |
| | Climate adaptive façade design with smart materials | Theory |
| | Climate adaptive façade a modular structure for office buildings | Theory |
| | Computational building performance simulation for integrated design and product optimisation | Energy |
| | Construction and control strategy of dynamic façade model of office building serve cold region | Energy |
| | Current trends and future challenges in the performance assessment of adaptive façade systems | Assessment |
| | Daylighting performance of an adaptive façade shading system integrated on a multi-story office building | Energy |
| | Design for façade adaptability towards unified and systematic characterisation | Theory |
| | Design of an adaptive shading system for arid climates: theoretical, numerical and experimental analysis | Theory |
| | Design optimum responsive façade based on visual comfort and energy performance | Energy/ Comfort |
| | Developing a design framework for climate responsive facades: material selection and performance metric identification | Theory |
| | Developing a strategic framework for the design of adaptive building envelope | Theory |

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|---|---|---|
| | Dynamic building envelope with PCM for cooling purposes. Proof of concept | Energy |
| | Effect of kinetic facades on energy efficiency in office buildings: hot and dry climate | Energy |
| | EKF based self-adaptive thermal model for passive house | Energy |
| | Energy matters in buildings: individual and collective issues | Energy |
| | Energy saving potential of long-term climate adaptive greenhouse shells | Energy |
| | Energy saving potential of climate adaptive building shells: inverse modelling of optimal thermal and visual behavior | Energy |
| | Evaluation of adaptive facades: a case study of swiss school in Dubai | Theory |
| | Evaluation of adaptive façade: the case study of AGC headquarter in Belgium | Theory |
| | Exploring the potential of climate adaptive building shells | Theory |
| | External shading in building: comparative analysis of daylighting performance in static and kinetic operation scenarios | Energy |
| | Framework for assessing the performance potential of seasonally adaptable façade using multi-objective optimisation | Energy |
| | Future climate adaptive building shells' optimising energy and comfort by inverse modelling | Energy |
| | How do bottom-up climate adaptive initiatives contribute to healthy environment in the city? A research into the possibilities of using a bottom-up strategy to achieve a healthy city | Urban Study |
| | How plants inspire facades. From plants to architecture: biomimetic principles for the development of adaptive architecture envelope | Theory |
| | Information storm: an assessment of responsive facades and their potential to introduce new relations between building users and the weather | Comfort/ Users |
| | Integrated parametric design for adaptive facades for users' visual comfort | Theory |
| | Interactive decision making environment for the design optimisation of climate adaptive building shells | Theory |
| | Mathematical modelling of performance of new type of climate adaptive building shell | Energy |
| | Models from nature for innovative building skins | Theory |
| | Numerical analysis of building envelope with movable phase change materials for heating applications | Energy |

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| | Optimum energy consumption by using kinetic shading system for residential buildings in hot arid areas | Energy |
| | Overview of 100 climate adaptive building | Theory |
| | Parametric behavior map: a method for evaluating the energy performance of climate adaptive building envelopes | Energy |
| | Performance simulation of climate adaptive building shells: smart energy glass as a case study | Energy |
| | Performance study of a multi-objective mathematical programming modelling approach for energy optimisation in building envelopes | Energy |
| | Post-occupancy evaluation for adaptive façade | Comfort/ Users |
| | Potential biomimetic applications of skin analogies on the building envelope. A conceptual approach for light intensity reactive heat energy screening | Energy |
| | Qualitative analysis of promising materials and technologies for the design and evaluation of climate adaptive opaque façade | Theory |
| | Responsive solutions in shaping innovative architecture structures | Theory |
| | Responsive building envelope as a material system of autonomous agents | Theory |
| | Responsive building envelope concepts in zero emission neighborhoods and smart cities: a roadmap to implementation | Urban Study |
| | Review and mapping of parameters for the early stage design of adaptive building technologies through life cycle assessment tools | Energy |
| | Review of current status requirements and opportunities for building performance simulation of adaptive facades | Energy |
| | Sustainable materialisation of responsive architecture | Theory |
| | Switching from static to adaptable and dynamic building envelopes: a paradigm shift for the energy efficiency in building | Energy |
| | Technologies compatible to climate change as a strategy in the field of architecture | Theory |
| | Temperature responsive system: passive strategies for building envelopes | Theory |
| | The potential of smart glazing for occupant well-being and reduced energy load in a central Mediterranean climate | Comfort/ Users |
| | The sustainability of adaptive envelopes: developments of kinetic architecture | Theory |
| | The thermal performance of residential building integrated with adaptive kinetic shading system | Energy |

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| | Thermal comfort and energy analysis of a window retrofit with dynamic glazing | Energy |
| | Towards environmentally responsive architecture: a framework for biomimicry design of building skin | Theory |
| | Towards predicting the satisfaction with indoor environmental quality in building performance simulation | Comfort/ Users |
| | User satisfaction and interaction with automated dynamic façade: a pilot study | Comfort/ Users |
| | Using building simulation for moving innovations across the Valley of Death | Energy |
| | Variable façade method to apply a dynamic façade solution in Santiago, Chile | Theory |
| | VII intonational congress on architectural envelopes biomimicry in climate adaptive building skins: relevance of applying principles and strategies | Theory |
| | What is an adaptive façade? Analysis of recent terms and definitions from and international perspective | Theory |
| | Simulation support for research and development of advanced building skin concepts | Energy |
| | Simulation-based support for product development of innovative building envelope components | Theory |
| | Smart solution for solar adaptive façade preliminary studies for an innovative shading device | Theory |
| | Superposition matrix for assessment of performance-relevant adaptive façade functions | Theory |
| | Sustainable assessment of smart materials in buildings | Theory |
| | Evaluation of adaptive facades: the case study of Al Bahr Tower in the UAE | Theory |
| | Evaluation of climate adaptive building shells: multi-criteria analysis | Energy |
| | Experimental assessment of the energy performance of an advanced responsive multifunctional façade module | Energy |
| | Experimental characterisation of adaptive transparent façade: lessons learned from three case studies | Theory |
| | Exploring the potential of smart and multifunctional materials in adaptive opaque façade systems | Theory |
| | Occupant-Facade interaction: a review and classification scheme | Theory/ Occupant-Centric |

<table>
<tr><td></td><td colspan="3">Development and validation of a survey for well-being and interaction assessment by occupants in office buildings with adaptive facades</td><td>Theory/ Occupant-Centric</td></tr>
<tr><td rowspan="11">Eligibility</td><td colspan="4">Records screened: 12</td></tr>
<tr><td>#</td><td>Section/topic</td><td colspan="2">Description</td></tr>
<tr><td rowspan="3">1</td><td>Title</td><td colspan="2">Post-occupancy evaluation of adaptive facades</td></tr>
<tr><td>Problem Formulation</td><td colspan="2">• There is a need for tools that empower users and help to solve those potential conflicts in adaptive façade operation and interaction between occupants, façade system, and other HAVC components.<br>• There is a serious need to use test facilities and simulation-based approaches that can help building operators to test, compare and improve POE methods and consequently, optimise CABS supervisory control strategies based on a variety of materials.</td></tr>
<tr><td>Recommendation</td><td colspan="2">For future studies, our findings can be useful for researchers in identifying new and industry relevant research area and for practitioners to learn from empirically investigated challenges in POE and base their improvement efforts on such knowledges. Identifying and investigating the overlaps underline the importance of these challenges and can also help in finding other research area enhancing POE for CABS.</td></tr>
<tr><td rowspan="3">2</td><td>Title</td><td colspan="2">Adaptive facades in temperate climates: an in-use assessment of an office building</td></tr>
<tr><td>Problem Formulation</td><td colspan="2">We could not fine any evaluation of comfort level in a building composed by adaptive facades in a temperate climate. A post occupation assessment of Media-TIC building is done to evaluate its performance and the perception of the users.</td></tr>
<tr><td>Recommendation</td><td colspan="2">More research in produce development and post occupancy assessment in buildings are needed to answer for complexity of office buildings in temperate climates, especially with adaptive facades, if we have to achieve low energy buildings and occupants comfort as some of the main goals of responsible buildings.</td></tr>
<tr><td rowspan="2">3</td><td>Title</td><td colspan="2">Information storm- An assessment of responsive facades and their potential to introduce new relations between building users and the weather</td></tr>
<tr><td>Problem Formulation</td><td colspan="2">Assessing how the users' experience of there envelope systems can create new relations between users and the weather by taking in the information generated by the weather and not just displaying it</td></tr>
</table>

| | | | |
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| | | | but making its dynamic apparent through the performance of envelope |
| | | Recommendation | - |
| | 4 | Title | Adaptive façade system assessment: an initial review |
| | | Problem Formulation | The appraisal of AF utilizing presently offer measuring and assessment guidelines raises a series of obstacles and concerns, including benchmark effectiveness and research methods, the richness and incorporation of AF with occupant reaction, HVAC system and control, innovation depiction and modeling information, and so on. |
| | | Recommendation | Future research should concentrate on choosing case studies of AF with thorough tracking performance data to better understand their performance and examine their optimisation possibilities. It is important to develop monitoring based benchmarks in order to inform professional and research community of gaps and needs of adaptive façade assessment. |
| | 5 | Title | Current trends and future challenges in the performance assessment of adaptive façade systems |
| | | Problem Formulation | Currently most adaptive facades are not designed with a user-centric approach |
| | | Recommendation | The role of adaptive façade in to make it possible for users to control their personal environment, privacy and/or view to outside to fulfil comfort needs. It is vital for adaptive façade post-occupancy evaluation to investigate the users' interaction opportunities or individual control with HVAC systems and BMS |
| | 6 | Title | Evaluation of adaptive facades: a case study of the Swiss School |
| | | Problem Formulation | Various actual projects including AF are being built across the world, but full analytical data on the functionality, design, and construction process of such facades is not easily accessible. The literature lacks specifics on completion and building confirmation, as well as performance statistics on AF' monitored operating performance and POE. |
| | | Recommendation | - |
| | 7 | Title | Evaluation of adaptive facades: the case study of AGC headquarter in Belgium |
| | | Problem Formulation | This study aims to present a case study from an AF and to generate maps of the fundamental decisions that went into how it was constructed, maintained, managed, and appraised. |
| | | Recommendation | To examine AF comprehensively, the operating energy cost and occupant comfort must be evaluated. This is why |

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| | | | COST Action TU1403 will request a POE for AGC construction as well as a variety of scientific proof performance indicators for this building. |
| | 8 | Title | The potential of smart glazing for occupant well-being and reduced energy load in a central Mediterranean climate |
| | | Problem formulation | The aim of the paper is to highlight the importance of occupants well-being from thermal and visual perspective, practically the need to maintain the availability of outlook from a building |
| | | Recommendation | Considering the reliability of current commercially available glazing products has been demonstrated through scientific research, their true effect on occupant well-being still needs to be investigated further, as only sparse precedent studies exist to date. |
| | 9 | Title | Towards predicting the satisfaction with indoor environment quality in building performance simulation |
| | | Problem formulation | The modelling approaches and occupancy scenarios that are available in traditional simulation programs are a simplified representation of reality; perhaps too simple for accurate IEQ models |
| | | Recommendation | |
| | 10 | title | User satisfaction and interaction with automated dynamic facades: a pilot study |
| | | Problem formulation | This paper presented the results of experimental research in pilot study setting, that aimed at gaining a better understanding of the relationship between automated dynamic facades and human factors. |
| | | Recommendation | Even though our results are based on an experimental set-up with internal roller shades, the results can be applied in a wider context. The diffusion into practice of other CABS technology, such as various types of kinetic façade elements, and emerging technologies like electrochromic glazing will face similar challenges in user interaction and occupant perception. |
| | 11 | title | Occupant-Facade interaction: a review and classification scheme |
| | | Problem formulation | Occupant-Facade interactions are often disruptive and source of dissatisfaction |

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| | | | because of conflicts between competing requirements, e.g. energy-efficiency and indoor environmental quality. |
| | | Recommendation | Novel classification scheme is proposed for multi-disciplinary research |
| | 12 | title | Development and validation of a survey for well-being and interaction assessment by occupants in office buildings with adaptive facades |
| | | Problem Formulation | Measuring occupant satisfaction is a developing issue in AF design practice, since there is a rising acknowledgment of the importance of occupant satisfaction in office buildings. |
| | | Recommendation | The research will be beneficial for benchmarking AF structures. |
| Included | 04 studies included in the qualitative synthesis | | 0 studies included in the quantitative synthesis |

Following Table 2, the official report of the PRISMA study according to official PRISMA documentation.

Table 2: Reporting a systematic review by PRISMA methodology (Author,2021)

| Section/topic | # | Descriptions |
|---|---|---|
| Title | 1 | The repost is a systematic review of literature with the keyword of climate adaptive building shells in order to support the existing gap in the knowledge. |
| Structured Summary | 2 | This systematic study has been done in order to support the problem formulation of an ongoing PhD thesis study. In this manner, based on the PRISMA method, literature existing in the data base has been screened, eligibility of the publications have been studied, and in the end the gap in the knowledge has been highlighted. In this field of Climate Adaptive Building Shells, most of the researches has the focus on field of energy or the theory and design of this system in general. But the main aim of designing a building, is to provide an pleasant space for the occupants. Study in satisfaction level of users in the main gap in the literature which by help of this PRISMA study, it could be highlighted in the clear way. |
| Rationale | 3 | The rationale of this study to highlight the excising gap in the literature and the need to work and fill this gap. During this systematic study, it has been highlighted that in many sources it mentioned still there is a need for post occupancy evaluation of CABS. And a method should be developing |

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| | | which can work with complexity of this system, and at the same time there is limited number of case studies. So there is no quantitative study in this filed. |
| Objectives | 4 | The main aim of this systematic study |
| Protocol And Registration | 5 | - |
| Eligibility Criteria | 6 | -publication on CABS<br>-In the English language<br>-from 2010 to 2020 |
| Information Sources | 7 | From the database: Springer, Science Direct, Research gate, Academia, google scholar |
| Search | 8 | For the research publication with the keyword of CABS, or the mentioned section of CABS/ ADAPTIVE/KINETIC has been found, throughout the screening of the publication they categorised in different filed of study, the ones with focus or if had mentioned POE, studied in deep and parts helping the problem formulation of the thesis highlighted |
| Study Selection | 9 | process for selecting studies: screening, eligibility, included in a systematic review. |
| Data Collection Process | 10 | method of data extraction from reports: independently |
| Data Items | 11 | - |
| Risk Of Bias In Individual Studies | 12 | This study will be used for synthesising the problem formulation of the ongoing PhD study. |
| Summary Measures | 13 | - |
| Synthesis Of Results | 14 | The key finding of this systematic investigation is that the problem indicated in the thesis is real, and there is a need to address this gap. |
| Risk Of Bias Across Studies | 15 | - |
| Additional Analyses | 16 | - |
| Study Selection | 17 | 113 publications have been found<br>10 has been removed after duplication<br>103 has been screened<br>12 publications studied as full publication for eligibility |
| Study Characteristic s | 18 | - |

| | | |
|---|---|---|
| Risk Of Bias Within Studies | 19 | - |
| Results Of Individual Studies | 20 | The result of the individual ten studies (in the eligibility section) shows a lack of research on POE in CABS. And several documented case studies in this field is needed. |
| Synthesis Of Results | 21 | This study has been a systematic review of literature not a meta-analysis. It clarifies the problem formulation of the thesis |
| Risk Of Bias Across Studies | 22 | - |
| Additional Analysis | 23 | - |
| Summary Of Evidence | 24 | The main finding of this review shows the main focus of the study on CABS has been mainly on energy efficiency, and the occupants' satisfaction/interaction and productivity has been neglected. It shows that there is a need for developing POE for CABS which can meet with the complexity of this system, and it should be put into practice since there is a lack of documented case study in this manner |
| Limitations | 25 | The limitation of this study is on just finding the mentioned problems and future study suggestions which can support the developed research problem for the thesis. |
| Conclusions | 26 | To be concluded, this review has successfully presented that this study's research problem is valid and needs to be worked. |
| Funding | 27 | - |

In this manner, this PhD thesis is trying to formulate a research problem around the development of POE for CABS based on the users' satisfaction, well-being, and productivity. Accordingly, POE and CABS have been studied in detail, and by considering the literature outcomes, a POE for CABS has been proposed.

## 1.2 Aim and Objective

Successful building design is becoming an increasingly complicated challenge because of the growing desire to meet more ambitious environmental, sociological, and economic performance objectives. CABS have lately been proposed as a possible option in the quest for better levels of sustainability in the built environment. However, there is no standardised assessment procedure for CABS, which creates a hurdle. Many existing shells performance evaluation methodologies and frameworks have limited relevance for such complex shells. The complexity of CABS evaluation is connected to the performance evaluation of shell elements, systems, overall building performance, and occupant behaviour and satisfaction.

Because of the facts highlighted by the literature review earlier, one of the obstacles to studying CABS based on user-centric principles is developing a thorough POE approach that can cope with the complexity of CABS. In this way, this study aims to analyse CABS and POE literature, highlighting the limitations of carrying POE for CABS and emphasising the importance of establishing innovative POE models that can deal with the complexity of CABS. The end result of this thesis can help researchers by filing a gap in literature, and the proposed model can be used for various researches and continually update the database of CABS according to the results provided by occupants. In the other hand, the evaluation of the results provided by model can help designers and practice of architecture. The evaluation of the results can present the general satisfaction level of occupants in one hand and after multi-criteria analysis based on various data added by researches to database the decision making for future CABS design can be done. By using the results from decision-making analysis, the future CABS designs can respond more positive towards occupants needs. The literature review involves summarising and comparing significant POE evaluations. Aside from an in-depth literature review, this study tries to address a gap in the literature about developing a POE framework that is suitable and beneficial for the CABS.

To summarise, the five primary scope of this PhD thesis are as follows:

- To present an in-depth literature review related to CABS and
- To present an in-depth literature review related to CABS and POE
- To analyse the most recent update of the CABS cases database and introduce a new taxonomy for CABS office buildings based on different variables and user-facade interaction; and
- To fill a gap in the literature related to developing a POE method or framework that can work with the complexity of CABS.
- Introducing appropriate data evaluation methods for occupant satisfaction and decision-making.

The following hypotheses were attempted to be answered throughout this PhD thesis:

- Hypothesis 1: A new taxonomy of CABS office buildings should include user-facade interaction,
- Hypothesis 2: Due to the lack of compatibility of traditional POE Methods with dynamic characteristic of CABS a dynamic POE model is required for assessing CABS occupant satisfaction,
- Hypothesis 3: Multi-domain and real-time data gathering and data evaluation must be considered for the POE model; and
- Hypothesis 4: Appropriate data evaluation methods must be used for future decision-making based on user-centric principles.

## 1.3 Research Methodology

This thesis performs qualitative research by concentrating on occupant-centric studies. Various methodologies were used in the preparation of the thesis. First and foremost, the PRISMA approach was used to clarify the study's problem statement. Later, using a descriptive research methodology, the literature of CABS and the most recent update of the cases database were analysed. A new taxonomy for CABS facade design was developed as a result. On the other hand, this thesis uses correlational research to identify the relationship between CABS and POE and emphasises the need for a unique POE model for CABS.

Lastly, this thesis uses a thematic analysis method to evaluate existing POE for CABS research topics by concentrating on occupant-centric studies. The following academic journal bibliographic databases are used for the literature review: Scopus, Web of Science (WoS), Google Scholar, and Research Gate. In all databases, the analysed articles must fit into one of the following categories:

- Studies are required to be based on the principle of occupant-centric research.
- Research should concentrate on determining occupant satisfaction and productivity.
- Studies should provide a qualitative and quantitative summary of POE for CABS.

Sets of keywords were selected and classified into two groups to conduct a literature review: a) occupant-centric studies of CABS (user satisfaction) and b) POE approaches for CABS (evaluation methods). Figure 3 depicts the scope of the study by presenting thematic analysis criteria and extracted keywords from the literature review.

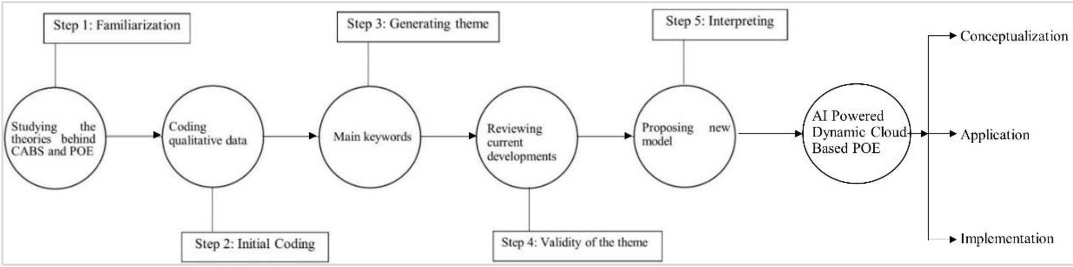


Figure 3: Thematic Analysis Methodology of the Research (Author, 2021)

The literature assessment emphasises recent achievements in this field of study and outlines a novel POE model's requirement to fulfil the CABS complexity. Consequently, a cloud-based dynamic POE model for CABS has been created. The conceptual model depicts the capacity to gather and analyse data in real-time, which is crucial for CABS due to their changing and adaptability over time. Finally, the study applies a multi-criteria analysis approach to propose a CABS decision-making system that can assist in determining the ultimate CABS system by taking technological, economic, and user considerations into account. This procedure will be feasible to pick the optimal CABS system to meet all sustainability pillars.

The model proposed for the thesis has been developed within three main sections of, Conceptualization, Application, and Implementation. For application of the model a supervised Machine learning method with help of surrogate model and ANN Architecture has been used. The data management system method used for the proposed model is developed according to relational data management method and Entity Relation Diagram Method.

## 1.4 Limitation of Study

As previously stated, the focus of this thesis is on the building shells. This research was built based on CABS (this approach is detailed entirely in the following chapter) and did not consider any traditional shell types. And, as for the function of the building, this thesis was conducted on office buildings alone, with no consideration for other building uses (residential, educational, health care and so on).

Another limitation has been placed on the evaluation methods. For this study, the POE methodology, which is the standard method for analyzing user experience in relation to outdoor and interior settings, was chosen from among various assessment approaches and frameworks. This technique assesses user interaction with the envelope, overall building performance, indoor environmental quality, and user satisfaction. By narrowing the scope of POE evaluations, this study focuses on the users' satisfaction, well-being, and productivity.

The work was completed by presenting a novel dynamic POE model for CABS by using supervised ML surrogate modelling and AAN Architecture, plus Relational data management method. The model has been developed by considering occupants as a sensor component of the model. The thesis discussing appropriate data evaluation methodologies for satisfaction assessment and decision-making. Due to Covid-19 outbreak, the model has not been applied in case studies within formulation of this thesis. However, the research aims to continue this study as a research project and apply the model on CABS cases.

## 1.5 Structure of the Thesis

This thesis is divided into seven chapters. The first chapter (Introduction) contains a broad introduction to the topic, formulation of the research problem, objectives and methodology, and the study's limitations.

The research then moves on to a comprehensive literature review of CABS and POE. Chapter two contains all of the information on CABS, including the definition of the system and its various characteristics. This chapter will propose a new categorisation strategy for user-façade interaction, one of the main phases of the research. Finally, a new taxonomy for CABS office buildings based on multi-domains will be introduced in chapter two.

The third chapter will concentrate on POE, the history and idea of this assessment technique, the benefits and characteristics of POE assessment method. In addition, they comprehend the notion and aspects of user satisfaction and its relationship to POE. By the end of Chapter 3, the variables for POE have been identified; identifying the variables demonstrates the necessity for more research into comfort factors and developing a new approach and model for POE.

The comfort criteria are covered in Chapter 4. This chapter examines four major comfort criteria and identifies comfort metrics. The identifying comfort parameters aid in the development of the questionnaire in Chapter 6. Following the literature assessment in chapters two and three, it was attempted in chapter five to link CABS, POE, and user satisfaction to build a framework for POE that can operate successfully for measuring the CABS users' satisfaction. Two alternate techniques to POE will be proposed in this chapter. Each strategy provides a foundation for the final model design. The first method emphasises the importance of real-time data collection, while the second chapter lays the groundwork for questionnaire design.

Chapter 6 is devoted to creating a new POE model for CABS. The suggested model is a cloud-based model that can collect real-time data and store it in the cloud using a sensor and a mobile app. The data will then be analysed using multi-criteria analysis, which will aid in decision making for the occupant-centric study on CABS. The questions in this chapter have also been created in two sets. The weight and value of each comfort parameter will be defined in the first section of questions (fixed questions). The second series of questions, which must be repeated, provides the overall degree of pleasure and the specific period of discomfort. It should be mentioned that the design of questions for the model has not been one of the main goals of this study, thus the validated questionnaire after various pilot studies, published as OCAFAS 15 has been used as an example for the possible questions. Finally, chapter seven presents the study's conclusion, which includes a review of the critical outcomes and suggestions for further research—following Figure 4 illustrating the thesis structure.

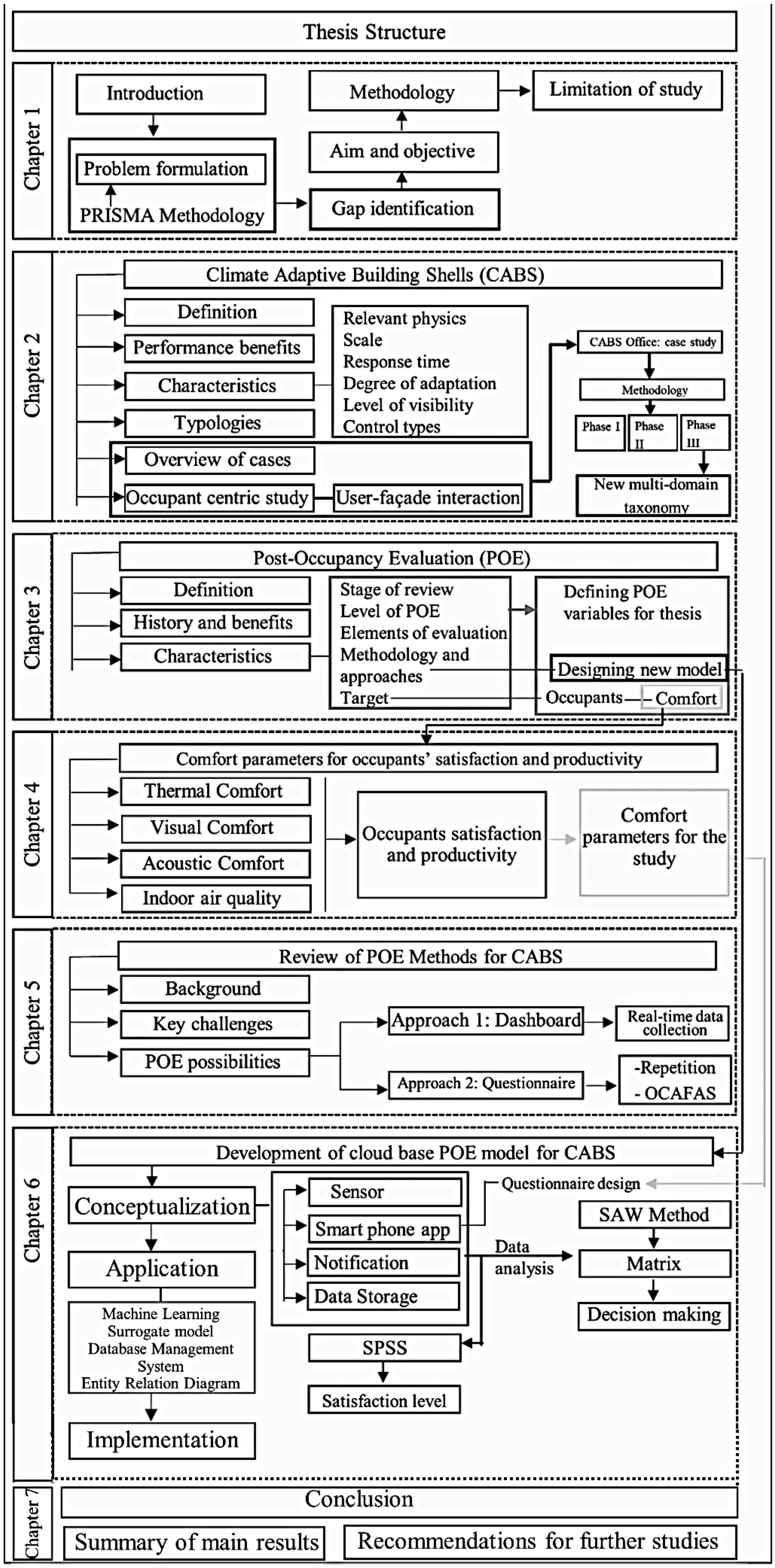



Figure 4: Structure of Thesis (Author, 2022)

# Chapter 2

# CLIMATE ADAPTIVE BUILDING SHELLS

Breakthroughs and advancements in building shell design are critical in narrowing the gap between the current state of building shell design and the ultimate aim of energy efficiency (Parasuraman and Hancock, 2001). Finding sustainable building design solutions is critical in a world confronting climate change, fast population rise, and daily increases in energy usage. The construction sector consumes more than 40% of all human energy consumption (Sieminski, 2015); hence, there is a need for technological advancements and the creation of new sustainable solutions in this area. The building shell plays an important part in this process. Various building shell design concepts have been presented and researched; however, climate adaptive building shells (CABS) are one of the most promising alternatives. CABS may be a game-changing design that substantially reduces a building's energy use while also attempting to meet the demands of its residents (Ahmadi-Karvigh et al., 2019).

CABS are built with dynamism and adaptability in mind. These shells can respond to climatic and environmental changes across various time frames (hourly, daily, seasonally or yearly). The first mention of this notion in the literature may be found in the 2007 research by Knaack et al. Various definitions have since been provided in the literature.

CABS were created with the goal of increasing the building's energy efficiency while also increasing occupant satisfaction and comfort. The primary purpose of CABS is to minimise building lighting and thermal load while attempting to create a comfortable atmosphere for inhabitants.

This chapter of the study examines the need for a transition from conventional façade to CABS by reviewing the literature in the field, analysing the CABD database. As the original outcome of this chapter, CABS office buildings based on user-façade interactions scenarios are categorised, and a novel taxonomy of these buildings are introduced. The investigation of CABS office buildings may be helpful in future case studies in this subject.

## 2.1 CABS v.s. Conventional Shells

Historically, buildings in different regions of the world did not have the same shape and design. No matter where it is located in the universe, the purpose of the building, particularly the building shell, is to shield the people from the surrounding environment. However, because the environment and available materials varied, the solutions were numerous. People made shelters appropriate for their environment and learned how to employ design and materials to improve the function of the, often modest, shelters. These distinctions are apparent when looking at vernacular architecture, commonly known as architecture without architects or shelters made by users and residents.

The emergence of the international style concept during the twentieth century, enabled by the development of the HVAC systems, empowered one united style worldwide. No matter where a building was located in the world, the building might pursue similar aesthetics. A skyscraper in New York, Singapore, or Beijing could look remarkably the same, notwithstanding the very different climatic conditions. Mechanical heat and ventilation systems handled the problems of heating, cooling, and air quality. This, of course, provided more individuals with the ability to customise their comfort, but at the expense of extremely high energy usage. HVAC systems not only use energy but are also known to cause discomforts, such as drafts and excessively dry air (De Boer et al., 2011). Because architectural design is no longer as firmly linked to climatic or environmental considerations, building design has become more about constructing a beautiful shape rather than something useful for comfort. Instead, the HVAC engineers were tasked with resolving the comfort issue. However, looking back at ancient ways of providing protection and comfort via design is an excellent place to start in an effort to lessen energy needs. The building's overall design and shell design could be more context-related and climatic-specific than today. The more a structure is tailored to a particular circumstance and the particular environmental loads that will affect it, the less time the mechanical system will need to intervene to maintain comfort. To do so, the designer must understand the environment and how the shell functions as a barrier between the outer and internal environments.

Throughout history, the building shell was often a homogeneous construction made of a single material or sometimes two. The shell's qualities were static and served as both thermal insulation and a structural load-bearing element. The notion of CABS has been advanced in recent years due to technological advancements. This technique considers the intricacy of design in the present day while also designing for unique climatic circumstances. The building's flexibility is more advanced than certain static norms. Thus, rather than relying on HVAC systems and static comfort standards, this technology acts on particular climatic parameters in each context to reduce the use of HAVC. As a result, the building's energy usage will reduce while still tries fulfilling occupant comfort criteria (De Boer et al., 2012).

It may be essential to evaluate the function of the building's enclosure in harmonising energy performance within the broader scope of total building performance. The majority of conventional building shells are constructed with the primary goal of providing shelter and protection in mind, which is frequently done by rendering the internal environment primarily indifferent to its surroundings. Building shells are placed at the interface between inside and outside and are therefore vulnerable to various changing environments. Meteorological conditions alter throughout the day and year, which relates to occupancy and comfort preferences.

Traditional building shell frequently have static characteristics and lack the ability to adapt to changes in the environment. Using CABS helps architects to take use of the available diversity. CABS has a considerable potential to lower the energy consumption of lighting and interior conditioning while also having advantageous effects on the level of comfort by improving IAQ by embodying the paradox of integrating the complementing characteristics of passive design with active technology (Attia and Bashandy, 2016).

## 2.2 Definition of CABS

CABS is only one name for a concept that goes by many various names. Figure 5 highlights the variants of the term "adaptive" found in the literature in this context. Although each of these statements has a somewhat distinct meaning, they are frequently used interchangeably. To prevent misunderstanding, the term CABS is used in this study and is defined as follows:

> Climate adaptive building shell has the ability to repeatedly and reversibly change its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions. By doing this, the building shell effectively seeks to improve overall building performance in terms of primary energy consumption while maintaining acceptable thermal and visual comfort conditions (Loonen, 2010).

Figure 5: Variation on the Theme “Adaptive” (Loonen, 2010)

The building shell is defined here as the construction components that constitute the interior and outside environment barrier. The building shell comprises both the opaque and translucent wall parts, as well as the roof. Adaptive behaviour in internal partitions, floors, and foundations is not taken into account. The roof design is commonly subordinated in everyday architectural practice and is driven by the fact that the roof of most structures falls outside the visual field of view. Nonetheless, their surface area is frequently more significant than the façade, and in terms of energy exchange, ignoring the roof’s contribution is unacceptable (Selkowitz et al., 2003).

The term ‘effectively’ is critical in the definition of CABS. This concept emphasises that performance variables should be addressed consciously in the design of adaptive behaviour rather than being based on ‘coincidences.’ Current shells are often built in layers, resulting in a breakdown of difficulties as well as a subdivision of only partial solutions (Knaack, et, al., 2008). According to Lichtenberg in 2005 (Gijsbers, 2006), the building has grown through a process known as “innovation by addition”; a technique that allows for significant advances. CABS attempt to reconcile the many performance factors more holistically. The layered approach to issue resolution is not what the CABS idea aspires.

Furthermore, the term “effectively” suggests some automatic—but not always automated—control. Too many projects have proved that, for example, installing blinds that occupants infrequently handle would not significantly improve performance (Reinhart and Voss, 2003, Mahdavi, 2008).

## 2.3 Performance Benefits of CABS

To produce suitable building designs, all functional needs (heat and airflow, noise, and so on) must be studied and met simultaneously. Because the requirements are so closely connected and sometimes even incompatible thus, this is not always an easy process (Rivard et al., 1995). The relative relevance of the various functional needs varies for each project and is determined by the project setting and the client’s demands. Nonetheless, all operating features are constrained by some minimal criteria, which are often specified in the form of building codes.

The technical efficacy of technology in a particular examination or collection of applications is referred to as its performance (Kolarevic and Malkawi, 2005). When this concept is used to 'building performance,' it entails considering both the environmental context and the interests of the numerous stakeholders engaged in the construction process. The Triple Bottom Line theory best exemplifies the performance of modern building shells (Figure 6). This business idea emphasises that a proper balance of performance qualities for people, planet, and profit must be attained for each successful technology.

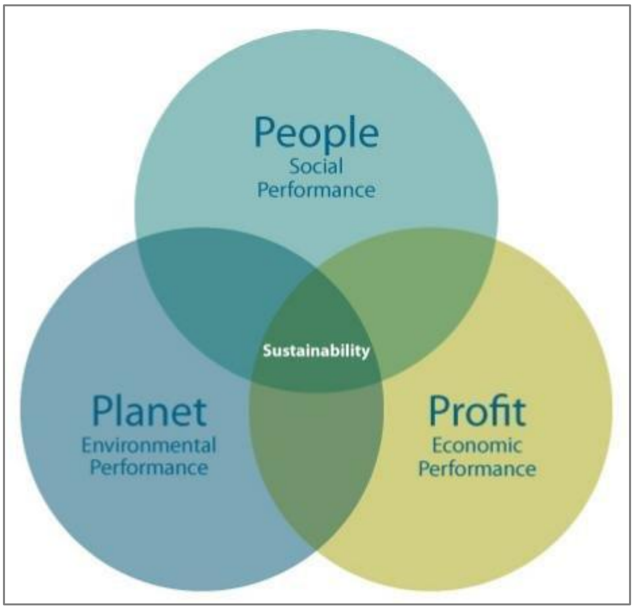


Figure 6: Triple Bottom Line (Saleh et al., 2009)

In an idealistic situation, the building shell is built in such a manner that the overall performance of the building is optimised in terms of environmental, economic, and social qualities. The environment of the building, on the other hand, changes throughout time, as do the desires of the occupants. Changes in building performance, by definition, occur in ways that deviate from what was planned. Buildings must be able to adapt to changing circumstances in order to continue providing satisfactory performance all year. As a result of the flexibility concept, CABS is a prospective solution to improve building performance based on the Triple Bottom Line suggestion.

Resiliency and flexibility are two design characteristics that allude to a system's capacity to manage change in general (Saleh et al., 2009). Unlike flexibility, robustness is frequently defined as a system's resistance or immunity to change. It is concerned with desensitising a system's performance, or quality attributes to changes in the system's environment while not removing the cause of these changes. CABS is a type of system that is created with flexible techniques in mind. As a versatile system, CABS possesses flexibility, multi-ability, and evolvability (Siddiqi and de Weck, 2008). As a result, this system provides performance advantages since it can adjust to both environmental and occupant demands as they vary over time.

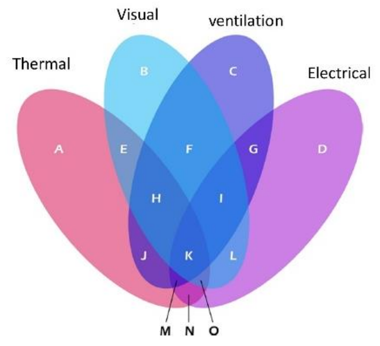
CABS, as previously said, may provide a beneficial impact to all three aspects: people (social), planet (environmental), and profit (economy). As CABS are used appropriately, they can save energy compared to traditional building shells. Because this reduces the demand for fossil fuel-based energy imports, reducing the stress on the ecosystem (i.e., planet). It has a direct impact on end users' energy expenditures (i.e., profit). A considerable number of CABS are also outfitted with building-integrated renewable energy-producing components. CABS' resource efficiency and the fact that CABS promote evolvability, which will most likely lead to extended building lives and help the environment and the economy. The performance advantages of CABS for individuals are commonly described in terms of better indoor environmental quality. This encompasses thermal comfort and occupant satisfaction with the lighting condition (visual comfort), acoustics, and air quality. Furthermore, growing data suggests that pleasant working spaces are related to higher levels of health and productivity (Heerwagen, 2000, Haynes, 2008, Wargocki, 2009). Focusing on offering high levels of comfort has a direct impact on the cost aspect as well.

## 2.4 Characteristics of CABS

After constructing a definition of CABS based on the literature and comprehending the significance of this system for building performance from all perspectives of the planet (environment), people (occupants, social), and profit (economy), it is necessary to go over the characteristics of this system to gain a better understanding of this system. As a result, themes such as the scale of adaptation, positioning of the CABS, physical relevance, control methods, etc., have been explored in this section. The categorisation seeks to put the various CABS in context with one another, revealing broad trends and patterns and variables that were crucial to the early implementations of CABS.

### 2.4.1 Relevant Physics

Building shells serve as the interface between the ambient environment and the interior zones and hence act as the subject of various physical interactions. Every CABS has its own unique means of influencing this multi-physical behaviour, such as blocking, filtering, converting, collecting, storing, or flowing through the various energy fields. Four domains are established to characterise the differences and similarities in CABS. In reality, the majority of CABS have an impact in more than one area. The four ellipse Venn diagram is used to depict the interrelations (Figure 7). Together, the four domains and all potential multi-physical overlaps provide a total of fifteen distinct possible variations to express the necessary physical interactions of a CABS idea. Other alternative domains, such as humidity and sound, were excluded since no examples could be discovered in the literature (Leung and Gage, 2008).




| | |
|---|---|
| Thermal | Adaptation causes changes in the energy balance of the building via conduction, convection, radiation and storage of thermal energy |
| Visual | The adaptive behavior influences occupants' visual perception via changes in the transparent surfaces of the building shell |
| Ventilation | A flow of air across the boundary of the façade is present, and adaptive behavior is influenced by the direction and speed of the wind |
| Electrical | Building-integrated energy generation takes place on the façade level, or electricity consumption is an essential part of the adaptation mechanism |

Figure 7: Description of the Physical Domains (Leung and Gage, 2008 amended by Author 2021).

### 2.4.2 Scale of Adaptation

There are two types of processes that promote adaptability in CABS. The adaptive performance is dependent on a change in attributes or behaviour at the macro or micro scale; however, variations are also conceivable. The spatial resolution at which adaptive actions occur distinguishes both systems, as discussed in greater detail below.

Macroscale adaptation in building shells is also alluded to as 'kinetic envelopes,' implying the presence of visible motion. Adaptation on a macro scale typically occurs in changes in the design of the building shell via moving elements (Erell et al., 2004) (Gan G, 2009, U.S. Office of technology assessment, 1979). Folding, sliding, expanding, hinging, and other gerunds are commonly used to represent the many forms of motion that may be witnessed.

Adjustments directly alter the internal structure of a material in the other form of CABS. Adaptability is demonstrated in this context either by alterations in thermophysical, opaque visual qualities, or the movement of energy from one form to another (Kurnitski, 2004).

### 2.4.3 Response Time

CABS system reaction times might range from a second to minutes, hourly, daily, seasonally, or annually. This reaction time might have an impact on the building's overall energy use. The effect of energy efficiency can be increased if the building is adaptive to any climate changes during the day (Leung and Gage, 2008).

### 2.4.4 Degree of Adaptation

CABS adaptation may be achieved in two stages: "Gradual" or using an "on-off" mechanism. The degree of adaptation in the on-off adaptability system is zero or 100, which signifies that the shading devices, for instance, are open or closed. On the contrary, adaptation occurs on a time scale and is progressive in the gradual adaptability degree. For example, the shading device may follow the course of the sun and continuously open or close regarding environmental changes over time (Leung and Gage, 2008).

### 2.4.5 Level of Visibility

In general, the adaptability level may be divided into three categories: "no viability," "low visibility," and "high visibility." As understood by the individuals, the visibility level refers to the degree to which the façade flexibility is perceptible. More specifically, the amount of visibility may be classified into five stages (Gan, 2009);

- Not visible, no surface change (ex: heat storage)
- Visible, no surface change (ex: smart glazing)
- Visible, surface change (ex: blinds)
- Visible, size or shape change (ex: dynamic façade elements)
- Visible, location of orientation change.

### 2.4.6 Control Types

Effective control is essential for the proper functioning of CABS. Studies distinguish two forms of control: extrinsic (close loop) and intrinsic control (Open-loop) (Figure 8).

The capacity to use feedback is a defining feature of CABS with extrinsic control. Feedback indicates that the present configuration (activity) results may be evaluated to the ideal outcome (set-point) and that the building shell's behaviour can be actively altered if required. Extrinsic (closed-loop) controlled CABS are comprised of three main components: sensors, processors, and actuators. A sensor is a technological element that can detect certain physical or chemical variables in the environment. The processor is the component responsible for collecting signals and data from all sensors and controllers. The third element, the actuator, is a 'tool' that translates control signal input into mechanical, chemical, or physical action (Addington and Schodek, 2005).

CABS with intrinsic control are distinguished by the fact that the adaptive capacity is an inherent element of the building shell's subsystems. CABS of this sort are self-adjusting since the adaptive activity is driven by environmental cues such as temperature, humidity levels, and so forth. As environmental influences are immediately translated into actions without the need for external decision making, this sort of remote control is also known as 'direct control' (Fox and Yeh, 1999).

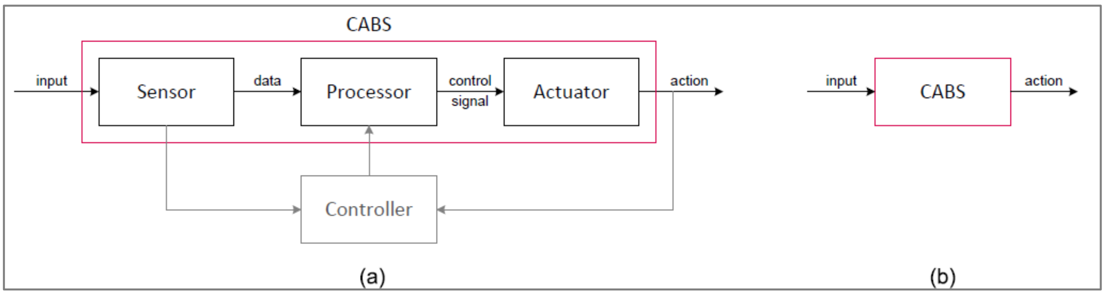


Figure 8: a) Closed-Loop Control b) Open-Loop Control (Addington and Schodek, 2005).

Compared to CABS with extrinsic control, intrinsic CABS have the benefit of being able to alter their configuration instantly without using any fuel or power to achieve the state transition. One major disadvantage of CABS with intrinsic control is that the systems can only adjust to anticipated alterations during the design stage. Additional limitations include the inability to perform manual interaction and integration with centralised high-level control systems (Addington and Schodek, 2005). Table 3 displays all of the technical factors and CABS characterisation ideas.

Table 3: Characteristics of CABS (Author, 2021)

| **Variables** | **Groups** |
|---|---|
| **Physical domain** | Thermal<br>Visual<br>Ventilation<br>Electrical |
| **Scale of adaptation** | Microscale<br>Macroscale |
| **Control types** | Intrinsic<br>Extrinsic |
| **Respond time** | Second<br>Minutes<br>Hour<br>Daily<br>Seasonally<br>yearly |
| **Degree of adaptability** | Gradual<br>On-Off |
| **Level of visibility** | Level 1: Not visible, no surface change<br>Level 2: Visible, no surface change<br>Level 3: Visible, surface change<br>Level 4: Visible, size or shape change<br>Level 5: Visible, location of orientation change |

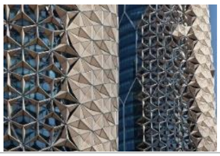
## 2.5 CABS Typologies

The emergence of new CABS variables adds new typologies to the field’s study. For researchers, a vast list of definitions such as passive, dynamic, kinetic, intelligent, switchable, interactive, moveable, smart, biomimetic, and so on that might substitute the phrase “adaptive” produces confusion (ElGhazi et al., 2017). While many of the terminologies stated fall under the umbrella of CABS, this Phase of the study attempted to describe each type shortly and highlight each typology’s connection with users to understand the issue better.

As a result of technological advances and improved control systems, there are examples of CABS that may be developed by overlapping more than one type. The responsive façade is the most sophisticated of all typologies in that it considers both interior and exterior environmental conditions when engaging with people (Velikov and Thün, 2013). Despite the fact that the central focus of this study is on the main umbrella of adaptable facades, “CABS,” it highlights the many terminologies and emphasises their interaction with users as given below in Table 4.

Table 4: CABS typologies (Tabadkani et al., 2021, amended by Author, 2021)

| **CABS Typologies** | **Descriptions** | **Developed from** | **User-façade Interaction** | | **Building example** |
|---|---|---|---|---|---|
| | | | **Yes** | **No** | |
| Active façade | Usage of active technologies,<br>Self-adjusting,<br>Improve energy savings | - | | X | Allianz Headquarter<br> |
| Passive façade | Passive design solutions,<br>No intelligent component | - | | X | Telefonica headquarter<br> |

| CABS Typologies | Characteristics | Developed from | User-façade Interaction | | Building example |
|---|---|---|---|---|---|
| | | | Yes | No | |
| Biomimetic | Imitated from plants and the human body,<br>Bottom-top or top-bottom approaches, | | | X | BIQ House in Germany<br> |
| Kinetic façade | Mechanical systems,<br>Actuation force is needed,<br>Acting based on outdoor environment condition | Moveable façade | | X | Al-bahar tower<br> |
| Intelligent façade | Ability to learn and respond in time,<br>Aautomatic and occupant control | Active façade<br><br>Smart façade | X | | GSW building<br> |
| Movable façade | Adjustable to environmental conditions,<br>Mobile systems, controlling the indoor environment or user comfort | | | X | Oval cologne office<br> |
| Responsive façade | similar performance characteristics to an 'intelligent' façade, self-adjust by educating the building and occupants progressively, usage of sensors, actuators, and control devices | Kinetic façade<br><br>Intelligent façade<br><br>Smart facade | X | | Kiefer Technic showroom<br> |
| Smart façade | operates either by changing internal physical properties or external exchanges, mostly combined with other types, | | | X | Thermochromic polymers- smart windows<br> |
| Switchable façade | Transparent components that can regulate energy and light flows, | Smart façade | X | | electrochromic glazing Rothschild Investment Bank<br> |

## 2.6 Overview on Applied CABS Cases

Many studies and activities on CABS have been conducted in recent years. According to the most recent CABS database updates, there are about 165 CABS cases. Despite growing respect for the conceptual features, the actual use of CABS in structures has remained restricted thus far. The variety of potential CABS technologies necessitated a methodical approach to accurately identifying and studying the façades. One of the major research projects relating to various elements of adaptable facades was completed in collaboration with the research group known as COST Action TU 1403. There have been four sub-groups in this group. Working Group 1 is in charge of the primary research on the CABS cases (Ferguson et al., 2017). The members of WG 1 took an analytic approach, defining higher standing structures within the façade (façade-systems) and recognising lower-rank sub-structures (components and materials) that built up the higher rank structures. In this sense, the database case studies were divided into three major categories (Figure 9) based on the following definitions:

- Material: material can be refined in various ways, such as raw, extruded, or coated. Materials that are inextricably bonded, such as bi-metals, also fall under this group.
- Component: component is an assemblage of several parts. As an element of a façade, it creates an entire constructional or functional unit.
- Façade-system: It consists of several translucent or opaque structural or technological elements. It meets all of the leading technical façade characteristics, such as insulation, rain and wind resistance (Aelenei et al., 2018).

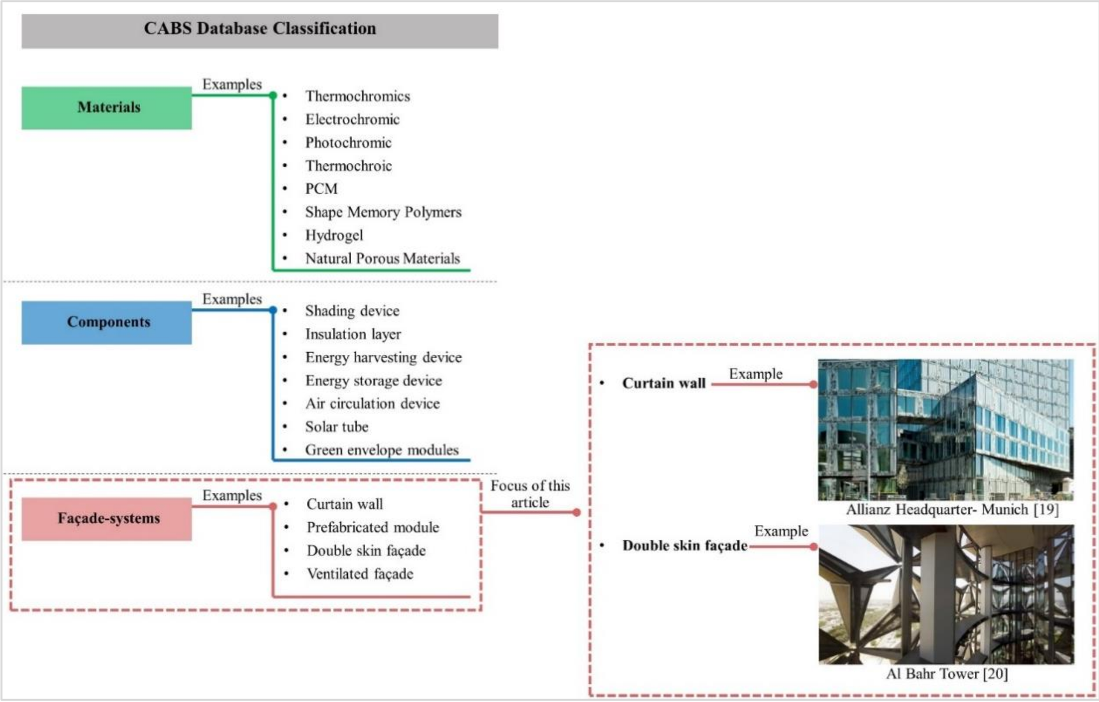



Figure 9: CABS Database Classification-Research Focus the Section (Aelenei et al. 2018, amended by Author, 2021)

The database created by cost Action TU1403 Working Group 1 contains 165 instances of adaptable façade systems, components, and materials that enable a wide range of evaluations. According to this investigation, the majority of data entries (41%) relate to the Facede system, followed by materials and component entries (32% and 27%, respectively). According to the statistics, most CABS buildings are large-scaled, with more than 34% larger than 5000 sqm. The most prevalent CABS type is double skin facades (30%), followed by prefabricated modular systems (32%). Thermal comfort was cited as the primary objective of the majority of CABS systems (30%), followed by visual comfort (24%). In terms of adaption time scale, most building adaptations occur within a second or minute time frame (49 per cent and 38 per cent). Statistics show that the most desirable feature of CABS is the ability to respond quickly to environmental changes. The reactive variety, most cases' visibility, has been introduced in the fourth level, which introduces noticeable changes in the size and form of the façade (with 42 per cent of cases). The map below (Figure 10), created by

Cost Action TU1403 WG1, shows the location of all 165 cases. According to this map, due to the sheer high expense of such technology, all CABS instances are situated in developed countries. The preponderance of the cases is from European countries such as Germany, the United Kingdom, and Switzerland (Ferguson et al., 2007).

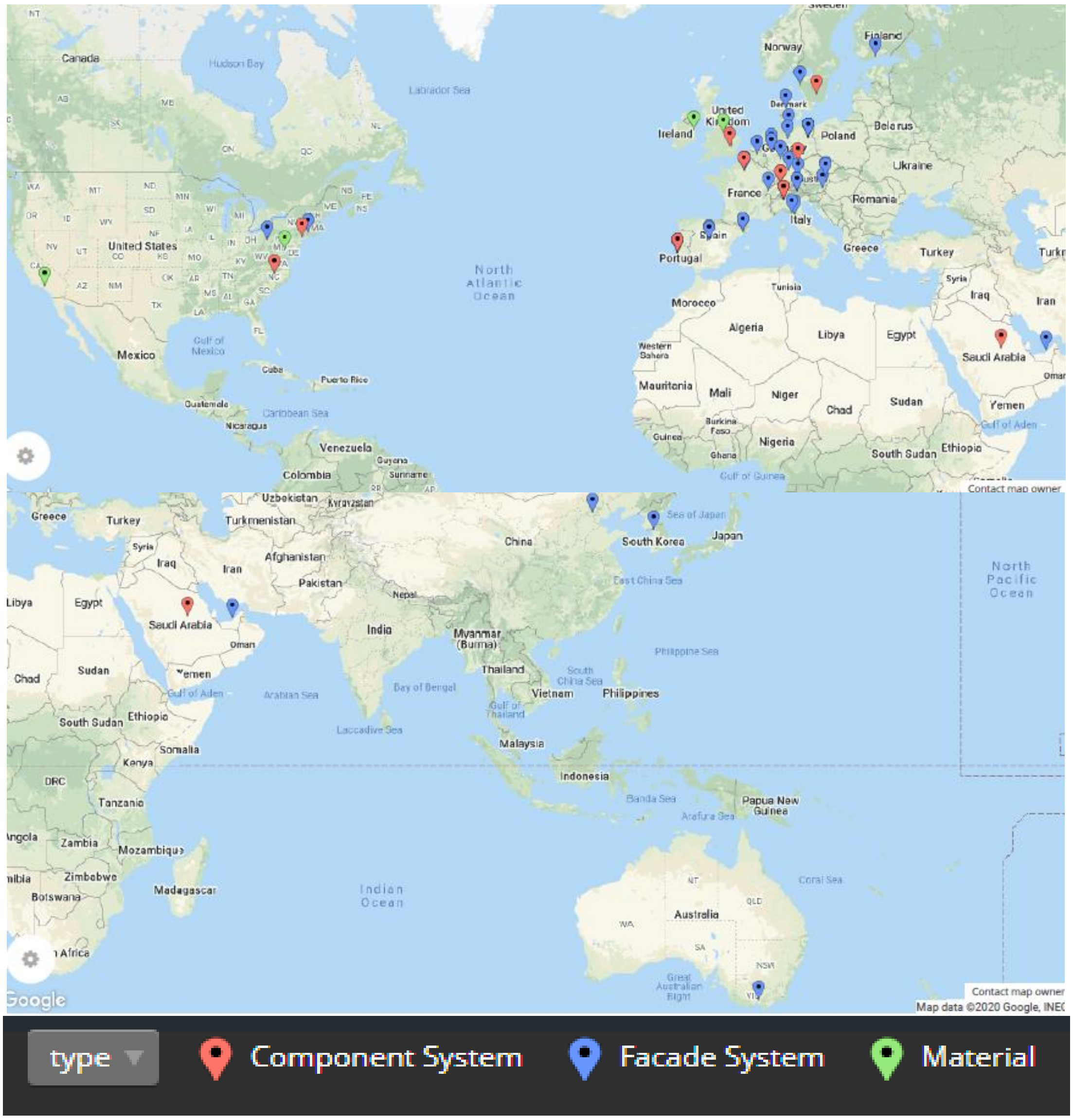



Figure 10: Location of 165 CABS Cases (retrieved from https:// batchgeo.com/map/ 5487a71fd294c2f8481412c474bcd668)

### 2.6.1 Methodology

An inductive research technique was employed to analyse CABS. By analysing and monitoring a large number of individual cases, this sort of research attempts to elicit the general characteristics of CABS (Figure 11). As a limitation of this study section, only “façade-system” examples were studied, and materials or components were excluded. A table was used in the next part to highlight the characteristic analysis of the cases.

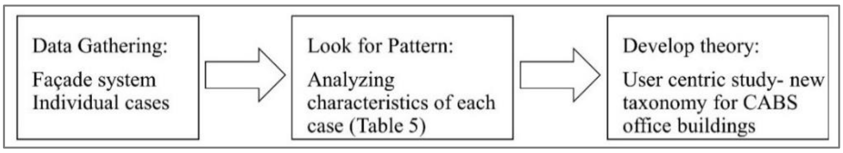


Figure 11: CABS Facade-System Case Study Methodology (Author, 2021)

### 2.6.2 Analysis and Results

The examination of the CABS façade system characteristics is shown in Table 5.
This table highlights the present state of CABS advances in architectural practice by highlighting all features of completed CABS façade systems.

Table 5: Analysis of “CABS façade systems” (Aelenei et al. 2018, amended by Author, 2021).

| **#** | **Building name** | **Function** | **Purpose (Physical domain)** | **Control** | | **Responsive time** | **Visibility level** | **Degree of adaptability** | **Scale** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | In. | Ex. | | | | micro | macro |
| **1** | Yale sculpture building | Office | Thermal, Visual Acoustic | x | x | Days Seasons | Level 01 | Gradual | x | |
| **2** | Oval cologne offices | Office | Thermal Visual | x | | Second Minutes | Level 04 | Gradual | | x |
| **3** | Palazzo lombardia | Office | Thermal | x | x | Minute | Level 02 | On-off | x | |
| **4** | Cyclebowl | Exhibition pavilion | Thermal visual | | x | Minute | Level 03 | Gradual | | x |
| **5** | Arab World Institute | Exhibition museum | Visual | | x | Second Minutes | Level 03 | Gradual | | x |
| **6** | Articulated cloud | Museum | Visual | x | | Second | Level 05 | Gradual | | x |
| **7** | Viagens Building/ Pt Building | Office | Thermal Visual Acoustic | | x | Second | Level 03 | On-off | | x |
| **8** | Campus Kolding | Office | Thermal visual | x | x | Second Minutes Hours | Level 04 | Gradual | | x |
| **9** | Allianz Headquarters | Office | Thermal visual | | x | Second Minutes | Level 03 | Gradual | | x |
| **10** | Hanwha Headquarters Remodelling | Office | Thermal Visual Acoustic | | x | Second Minutes | Level 01 Level 02 | Gradual | x | x |
| **11** | Nordic embassies in berlin | Office | Thermal Visual | | x | Minutes | Level 04 | Gradual | | x |
| **12** | MEDIA-TIC | Office | Thermal Visual | | x | Minutes | Level 04 | Gradual | | x |
| **13** | KFW westarkade | Office | Thermal Visual | | x | Minutes | Level 04 | On-off | | x |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **14** | Head office of AGC glass Europe | Office | Thermal<br>Visual | x | | Second | Level 05 | On-off | | x |
| **15** | Nursing home meidling | Healthcare | Visual | | x | Minutes | Level 04 | Gradual | | x |
| **16** | Office building friedrichstrasse 40 | Office | Thermal<br>Visual | | x | Minutes | Level 04 | Gradual | | x |
| **17** | KUGGEN | Office | Visual | | x | Minutes | Level 05 | Gradual | | x |
| **18** | nZEB office building ympäristötalo | Office | Thermal | x | x | Minutes | Level 02 | Gradual | x | |
| **20** | Museion, Bolzen | Museum | Thermal<br>Visual | | x | Minutes | Level 04 | Gradual | | x |
| **21** | GSW Headquarters | Office | Thermal<br>Visual | | x | Minutes | Level 04 | Gradual | | x |
| **22** | Altis Belém Hotel | Hotel | Thermal<br>Visual | | x | Minutes | Level 04 | Gradual | | x |
| **23** | Bahn Tower | Office | Thermal<br>Visual<br>Acoustic | | x | Minutes | Level 04 | Gradual | | x |
| **24** | European Academy | Research centre | Thermal<br>Visual<br>Acoustic | | x | Minutes | Level 01 | Gradual | x | |
| **25** | Fünf Höfe | commercial | Visual | | x | Minutes | Level 03 | Gradual | | x |
| **26** | The National Library of France | Cultural building | Thermal<br>Visual<br>Acoustic | | x | Minutes | Level 03 | Gradual | | x |
| **27** | Information communication technology centre | Office | Thermal<br>Visual<br>Acoustic | | x | Minutes | Level 03 | Gradual | | x |
| **28** | The Algaehouse | Residential | Energy | | x | Hour | Level 02 | Gradual | x | |
| **29** | Kiefer Technic Showroom | Office | Thermal<br>Visual | | x | Seconds | Level 03 | Gradual | | x |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **30** | Aalen University Extension | Educational | Thermal<br>Visual | | x | Seconds | Level 03 | Gradual | | x |
| **31** | Carabanchel Social Housing | Residential | Thermal<br>Visual | | x | Seconds | Level 03 | Gradual | | x |
| **32** | Telefonica Headquarters | Office | Thermal<br>Visual<br>Acoustic | x | | - | Level 01 | - | x | |
| **33** | ENERGYbase | Office | Thermal<br>Visual<br>Acoustic | x | | Minutes | Level 01 | On-off | x | |
| **34** | Fire And Police Station Berlin | Office | Thermal<br>Visual<br>Acoustic | | x | Minutes | Level 03 | On-off | | x |
| **35** | Solar XXI – BIPV/T Systems | Office | Thermal<br>Visual<br>Acoustic, Energy | | x | Hour<br>Season | Level 01 | On-off | x | |
| **36** | RMIT Design Hub | Office | Thermal<br>Visual | | x | Minutes | Level 03 | Gradual | | x |
| **37** | SELFIE Facade | Office | Thermal<br>Visual<br>Acoustic, Energy | x | x | Minutes | Level 01 | Gradual | x | |
| **38** | Swisstech convention center western facade | Convention centre | Visual | x | | Second | Level 01 | On-off | x | |
| **39** | Agbar Tower Barcelona | Office | Thermal<br>Visual | x | | Minutes | Level 03 | Gradual | | x |
| **40** | Al Bahar Towers | Office | Thermal<br>Visual<br>Acoustic | x | | Minutes | Level 04 | Gradual | | x |
| **41** | Thyssenkrupp Quarter | Office | Thermal, Visual<br>Acoustic | x | | Minutes | Level 03 | Gradual | | x |

The table above provides a general knowledge of the evolution of the CABS façade systems. This technique has been chiefly used in office buildings. Of the 41 cases, 28 (68 per cent) are office buildings. Aside from the function of the structures with this system, it is clear that this system has evolved mainly through the Extrinsic control type, Macroscale adaptation. The majority of the time, the adaption visibility is apparent at levels 03 and 04 with a gradual degree. Typically, the adaptation time is less than a minute or a second. As a result, the shells reacts to changes in the surroundings. The following graphs show the results of the case studies (Figure 12).

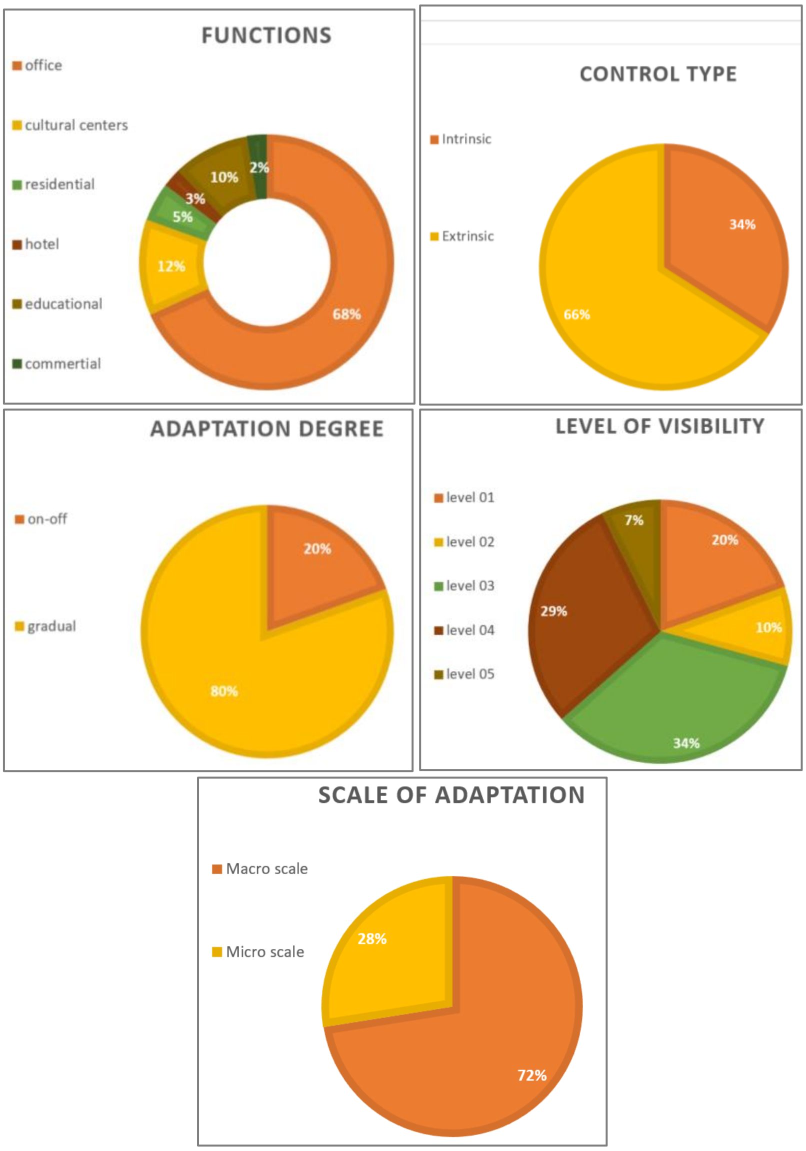



Figure 12: Analytical Charts of CABS Façade System Analysis (Author, 2022)

## 2.7 Occupant-Centric Study Concept

Occupants have an active role in their built environment, influencing its operation while also being influenced by its design and interior environmental circumstances. Topics such as human-building interactions and occupant behaviour have attracted substantial interest in the literature due to recent developments in computer modelling, simulation tools, and analytic methodologies, with the premise of enhancing building design processes and operation tactics.

An accurate “occupant-centric” study puts the user first regarding occupant acceptability, comfort, and satisfaction. To address the topic of how a building might improve the human experience through high functionality or innovation, it’s vital first to consider occupants as the ultimate goal of a building design.

By employing the concept of occupant-centric research, this PhD thesis places the occupants at the centre of attention; thus, it was first attempted to review the occupant-centric studies in this field to highlight the synthesis of the studies and underline the following need for additional research in this field. Later, analysing user-façade interactions and classifying the CABS office building based on those findings.

### 2.7.1 CABS Literature Review with Occupant-Centric Focus

This technology provides a solution that satisfies the aim of reducing energy use. Consequently, most attention given to the energy consumption studies and detailed research on this system to provide actual value from occupant satisfaction and engagement is lacking in the literature (Smith et al., 2001). There is still a question mark in the study field of this system: “Are occupants satisfied with having less control over the building’s façade?”

Various fields are involved in occupant-centric research and user-façade interaction with CABS, including a) social science, b) environmental psychology, c) computer science, d) economics, and e) building science. Despite the fact that a range of research in the stated areas have been conducted, multi-dimensional studies on the impact of adaptive systems on users are restricted to date (Stazi et al., 2017).

Various researchers attempted to discover answers to the aforementioned concerns through various but restricted inquiries on the building science profession. Table 6 below summarises the purpose and synthesis of these investigations, as well as the limitations of each. Currently, the literature on CABS connected to occupant-centric research is insufficient and fails to convey the complexities of this system and its relationship with the occupants.

Meerbeek et al. (2014) provided one of the first studies on CABS with an eye on occupant-centric research. Within five months, they conducted a qualitative and quantitative study on 40 Dutch office buildings. The study's findings indicate that occupants are uninterested in automating façade controls. However, Meerbeek et al. 2014's research and several other comparable studies do not address the intricacy of CABS and the multi-disciplinary and complicated interaction between occupants and façade. In such complex relationships, multi-domains can have an impact on user satisfaction and productivity. However, Meerbeek et al. 2014's study on automation shading control systems shows an insight into the need for comprehensive and multi-domain research on CABS and occupants' needs, satisfaction level, interaction, and productivity. Such a study proposes the best CABS to fulfil energy efficiency goals and promote occupant satisfaction (Meerbeek et al., 2014).

Aside from Meerbeek et al. 2014's study, there have been two interdisciplinary investigations on this topic. The first research was conducted in 2017 by D'Oca et al., and the second in 2016 by Von Grabe. Although both studies attempted to take a multi-disciplinary approach to fill a gap in the research, they fell short in highlighting the consequences of proposed alternatives on occupants. Table 6 below provides an overview of current research on this topic. At the same time, they emphasised the necessity for more extensive occupant-centric studies.

Table 6: Review on CABS occupant-centric studies from a building science point of view (Author, 2021)

| **Title of publication** | **Aim** | **Main focus** | **Conclusion and synthesis** | **Complexity of research** |
|---|---|---|---|---|
| Intelligent facades: occupant control and satisfaction (Stevens, 2001) | Investigate the user satisfaction and impact of user control in intelligent facades | Occupant control | Users' satisfaction affecting by user s control in intelligent facades buildings | Not considering the complexity of different CABS types |
| Patterns of occupant interaction with window blinds: A literature review (Wymelenberg, 2012) | Reviewing acceptance of users for automatic blinds. | operate blinds | Highlighting the gap in the literature and suggesting further researches | Not a multi-discipline study. |
| The contextual factors contributing to occupants' adaptive comfort behaviours in offices – A review and proposed modelling framework (O'Brien and Gunay, 2014) | Presenting a framework for studying occupants' behaviour. | Occupants behaviour | Synthesis of the occupant behaviour literature. | No synthesis about interaction effects on users' behaviour and satisfaction |
| User satisfaction and interaction with automated dynamic facades: A pilot study (Bakker et al., 2014) | Investigating the user satisfaction in buildings with automated facade | User satisfaction | Synthesising the further need for adaptive façade algorithm development | Not considering the complexity of different CABS types.<br>Not considering user interaction with a facade |
| Building automation and perceived control: A field study on motorised exterior blinds in Dutch | Underling the users' behaviour on the usage of different blind | Occupants behaviour-Venetian blinds | The automatic mood has not to be preferred | Not a multi-discipline study. |

| | | | | |
|---|---|---|---|---|
| offices (Meerbeek et al., 2014) | | | | |
| The systematic identification and organisation of the context of energy-relevant human interaction with buildings—a pilot study in Germany (Von Grabe, 2016) | aims to address: which contextual factors are impactful? And which methods are best suited to predicting energy-relevant interaction based on the knowledge of these contextual factors? | Multi-disciplinary framework | Concluding with identifying the context of energy-relevant user interaction with the facade | It does not mention how this alternative affect occupants |
| Review of current methods, opportunities, and challenges for in-situ monitoring to support occupant modelling in office spaces (Gilani and O'Brien, 2017) | Reviewing the users' behaviour in the context of existing buildings | Occupants behaviour | Recommendations for further studies | No synthesis about satisfaction level.<br>Interaction effect on users |
| Synthesising building physics with social psychology: An interdisciplinary framework for context and occupant behaviour in office buildings (D'Oca et al., 2017) | Investigating the occupants' adaptation behaviour and building control | interdisciplinary framework | Highlighting the human-building interaction knowledge in office buildings. | Dose does not mention how this alternative affect occupants |
| A literature review on driving factors and contextual events influencing occupants' behaviours in buildings (Stazi et al., 2017) | Highlighting the literature review related to occupants behaviour | Occupants behaviour | Presents that besides environmental factors, contextual factors have effects on occupants behaviour | No synthesis about satisfaction level. |
| Occupancy-based lighting control in open-plan office spaces: A state-of-the-art review (de Bakker et al., 2017) | Investigate the occupancy-based lighting control | Lighting control | Further validation is needed for occupancy-based lighting control. And acceptancy level of it by occupants should be studied. | Not a multi-discipline study. |
| One size does not fit all: Understanding user preferences for building automation systems | Investigating the preference of users for control of lighting systems in residential buildings. | Lighting | In all contexts, no automation over lighting control has been the least preferred. | Not a multi-discipline study. |
| Ten questions concerning occupant behaviour in buildings: The big picture | Presenting questions addressing the most critical aspects related to users behaviour | Occupants behaviour | Highlighting an insight related to users behaviour | Not a multi-discipline study. |

| | | | | |
|---|---|---|---|---|
| (Ahmadi-Karvigh et al., 2017) | | | | |
| Comprehensive analysis of the relationship between thermal comfort and building control research - A data-driven literature review (Park and Nagy, 2018) | Reviewing two research fields of; optimal building operation (control) and users' thermal comfort. And studying their relation | Thermal comfort | Building controls focus on the building energy consumption rather than the thermal comfort of users | Not a multi-discipline study. |
| A review of occupant-centric building control strategies to reduce building energy use (Naylor et al., 2018) | Reviewing building control systems and advanced occupant-centric controls. | HVAC | suggest an optimum point balancing the complexity of a system against its potential for saving energy | Not a multi-discipline study. |
| A review of a smart building sensing system for better indoor environment control (Dong et al., 2019) | Reviewing the building sensors and managing the energy-saving, users comfort and IAQ | Sensors | Further studies are needed to cover the complexity of the topic and find a satisfying level in the real-time | Not a multi-discipline study. |
| Human-in-the-loop HVAC operations: A quantitative review on occupancy, comfort, and energy-efficiency dimensions (Jung and Jazizadeh, 2019) | Reviewing the hierarchical taxonomy, based on their contributions to occupancy- and comfort-driven human-in-the-loop HVAC operations | HVAC | The hype cycle model was utilised to qualitatively evaluate the developments of different technologies for human-in-the-loop HVAC operations from a research perspective. | Not a multi-discipline study. |

The variety of options and alternatives for user-façade interaction has risen due to CABS' ongoing technical improvements. As a result, in many circumstances, occupants may overcome the façade and interact with the control systems. In some scenarios, the façade may analyse the demands and behaviour of the inhabitants over time and manage adaption based on occupants and environmental parameters (Bradshaw et al., 2003). As a result, the study of occupant satisfaction is more extensive than that reported by Meerbeek et al. in 2014 or other investigations stated in the preceding table.

Identifying the many sorts of user-façade interactions is very important because it is a crucial indicator of user satisfaction. Investigating this element can aid in determining the actual value of CABS and the best option for the occupants' demands. Throughout the broad timeline, the literature evaluation demonstrates a clear relationship between occupant satisfaction and interaction with façade. According to several research, even though CABS improves the indoor environment and increases energy efficiency, in other situations, occupants' satisfaction is reduced due to a lack of engagement with the façade (Ahmadi-Karvigh et al., 2017). Previous studies on CABS cannot capture the complexity and multi-disciplinary occupants' interaction with this system. The majority of investigations on occupant-façade interaction concentrated on a single domain. For example, they are concentrating on inhabitants and thermal comfort. As a result, understanding all alternative variations for user-façade interaction in this system is critical (Stevens, 2001).

### 2.7.2 User-Façade Interaction

As previously stated, CABS is a potential option for accomplishing the objective of sustainability in design. So far, the technological aspects of this system have been thoroughly examined. According to the PRISMA research in Chapter 1, the significant attention on investigating CABS has been dedicated to the energy performance of this system and occupant's centre studies are neglected. As a result, without understanding the interdisciplinary complexity of the user-façade interaction in this system, successful CABS solutions that provide an optimal balance of user comfort, satisfaction, and energy efficiency cannot be attained. The multi-domain relation between buildings' users and building façade is a complex relationship which many factors can affect it (Loonen et al., 2013). In this manner, the studies and researches focusing on users and their interaction with building façade is still limited and unknown (Luna-Navarro et al., 2018). Figure 13 depicts the relationship between the façade, the user, and the building management. The initial goal and focus of this research is on the interaction between users and façades.

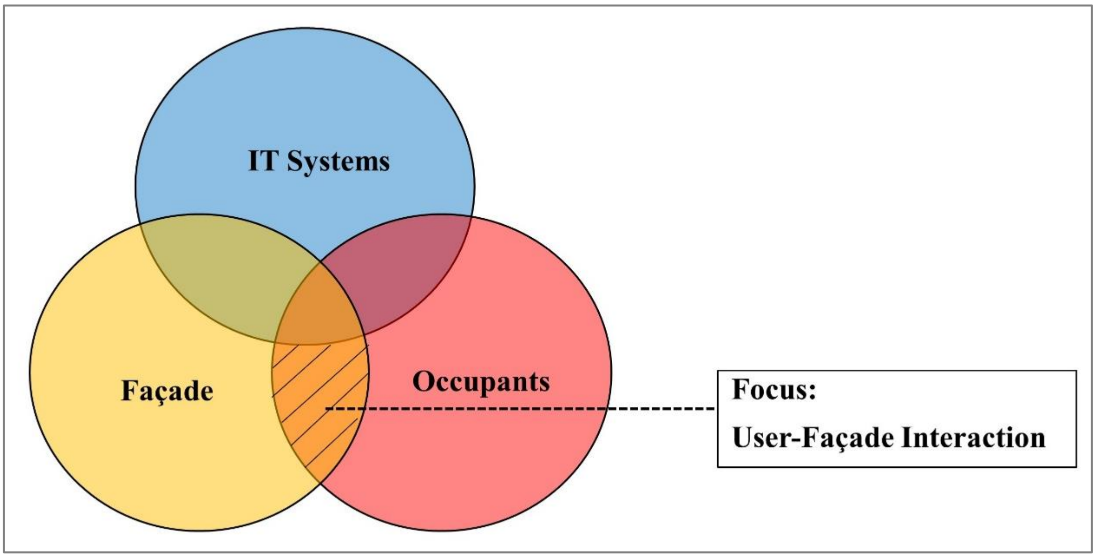



Figure 13: Multi-Disciplinary and Interrelations of Façade, Occupant and IT System (BMS) (Luna-Navarro et al., 2018).

### 2.7.2.1 Relationship and Conflict Between Façade and Occupants

To date, the main concentration in this field (user-façade interaction) is focusing on the connection and relationship of the buildings' occupants and the operation of the system. As an example, the study of Wymelenberg can be mentioned which presents an analysis on buildings' users and operation of window blinds. Or as similar study, Fabi et al. in 2012 analyzed the behavior of buildings' users over opening the windows. Such studies highlight that, the problems are usually focusing on few aspects: a) control of the buildings occupants over façade and their understanding about the operation mechanism of the system; b) continues influence of the system on users; and c) disputes among different occupants in the shared spaces (Stazi et al., 2017).

In general users' lack of knowledge about the system can cause on higher environmental impacts, increase the general energy consumption of the building and at same time decrease the level of satisfaction. Occupant instruction on building operations techniques is critical in this regard, as demonstrated by Day and Gunderson (2015), who found that occupants who received training programs were much happier with their workplace environment. Occupants' misinterpretation of the individual control system can frequently result in excessive environmental discontent, while also weakening passive energy-efficiency efforts (Ackerly and Brager, 2013).

Different changes on the façade can have direct impact over variety of environmental factors, in this manner, it is common that occupants comfort criteria and their demands be neglected in order to find the required balance for façade performance. For example achieving the acoustic comfort required by users might be in the opposite side of achieving natural ventilation which can help energy demand of the building (Loonen et al., 2013). In this context, studies on the causes for user behavior inspired by despair are useful in guiding automatic control techniques regarding which control to deploy, even in conflictive circumstances (Fabi et al., 2012).

#### 2.7.2.2 User-Facade Classifications and Scenarios

The increasing number of adaptive/intelligent building components has enhanced the number of interactions occupants may have with building elements. For example, residents may now engage with and actively influence automatic building control techniques (Selkowitz, 2017). In addition, automated or intelligent control devices can monitor occupant behaviour and reaction in order to adjust to and learn from people's everyday routines (Jäger et al., 2016).

Buildings' users are able to change the interior environment condition directly through the façade (Bakker et al., 2014). The buildings' users control and interaction with the façade performance can directly decrease or increase their satisfaction level (Brager et al., 2004).

Alessandra et al. (2020) 's study, one of the most advanced researches in the field, aims to create a categorisation framework that encompasses the variations and permutations of Occupant-Facade interactions and analyses different interacting scenarios from the occupant's perspective.

In this regard, the first item that must be defined is the type of façade and its actuation mechanism. The shell types may be divided into two categories: static and dynamic. There is no actuation mechanism in the static shell type, and this kind is not the subject of the thesis study. The second category is dynamic, which involves at least one sort of actuation. Actuation systems can be self-adjusted and manual (intrinsic material qualities, local control, and so on) or automated (environmental sensing, occupant centre) (Table 7).

Table 7: Type of actuation system (Alessandra et al., 2020)

| **Presence of actuation mechanism** | **Type of actuation mechanism** | **Mode of actuation** |
|---|---|---|
| **STATIC** | Self-adjusted | Intrinsic material properties<br>Local control<br>Remote control |
| **DYNAMIC** | automated | Environmental sensing<br>Occupant-center |

A new categorisation method was designed in 2020 based on the research of Alessandra et al. The categorisation method defines four major physical components: the occupant (O), as a single or group, the control Logic or "Operating system" of the

CABS and automation system (L), the hardware or physical array of façade components (F), and the Building Services (B). “B” refers to artificial lighting, heating, cooling, and ventilation systems. There is a contrast between traditional rule-based Logics (L) and learning Logics (Lm), which correlate to automated systems without and with AI-enhanced features. Due to the variety interaction types between the different elements many unique interactive environments can be created. The proposed categorization can be generalized within two main groups according to different objectives: Direct Interactions (I) where a direct request of action, feedback or information display is made between two physical components and Automatic Sensing, where there is an indirect interaction between two physical components through sensing devices (S) (Alessandra et, al, 2020) (Figure 14).

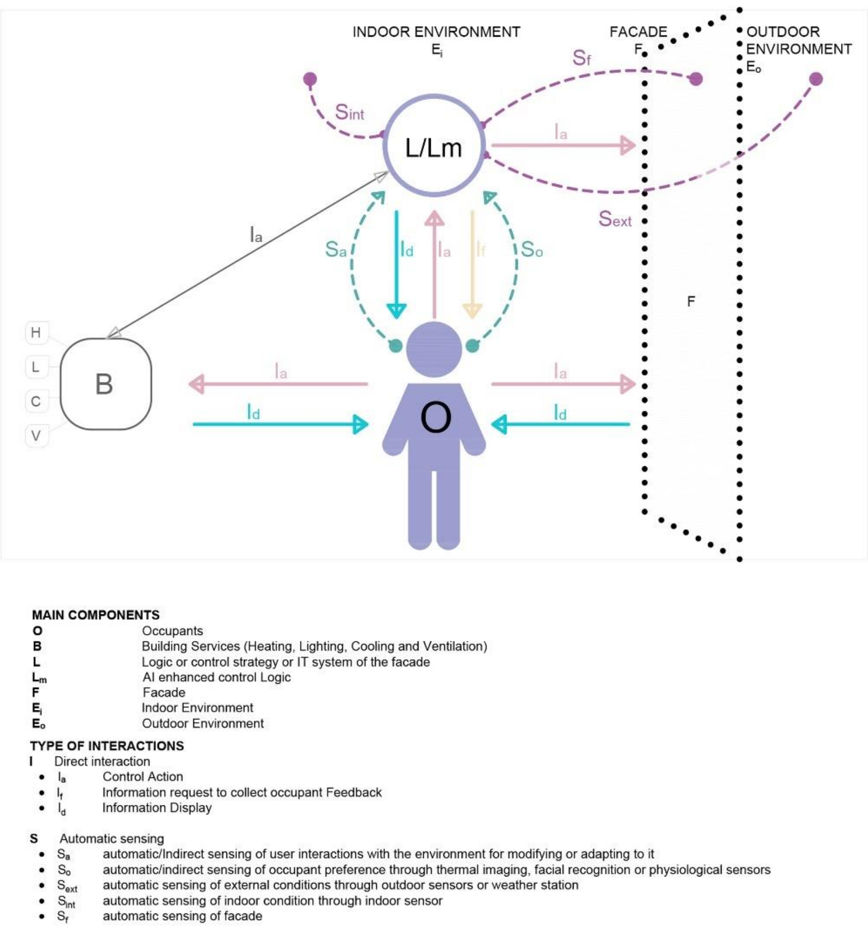


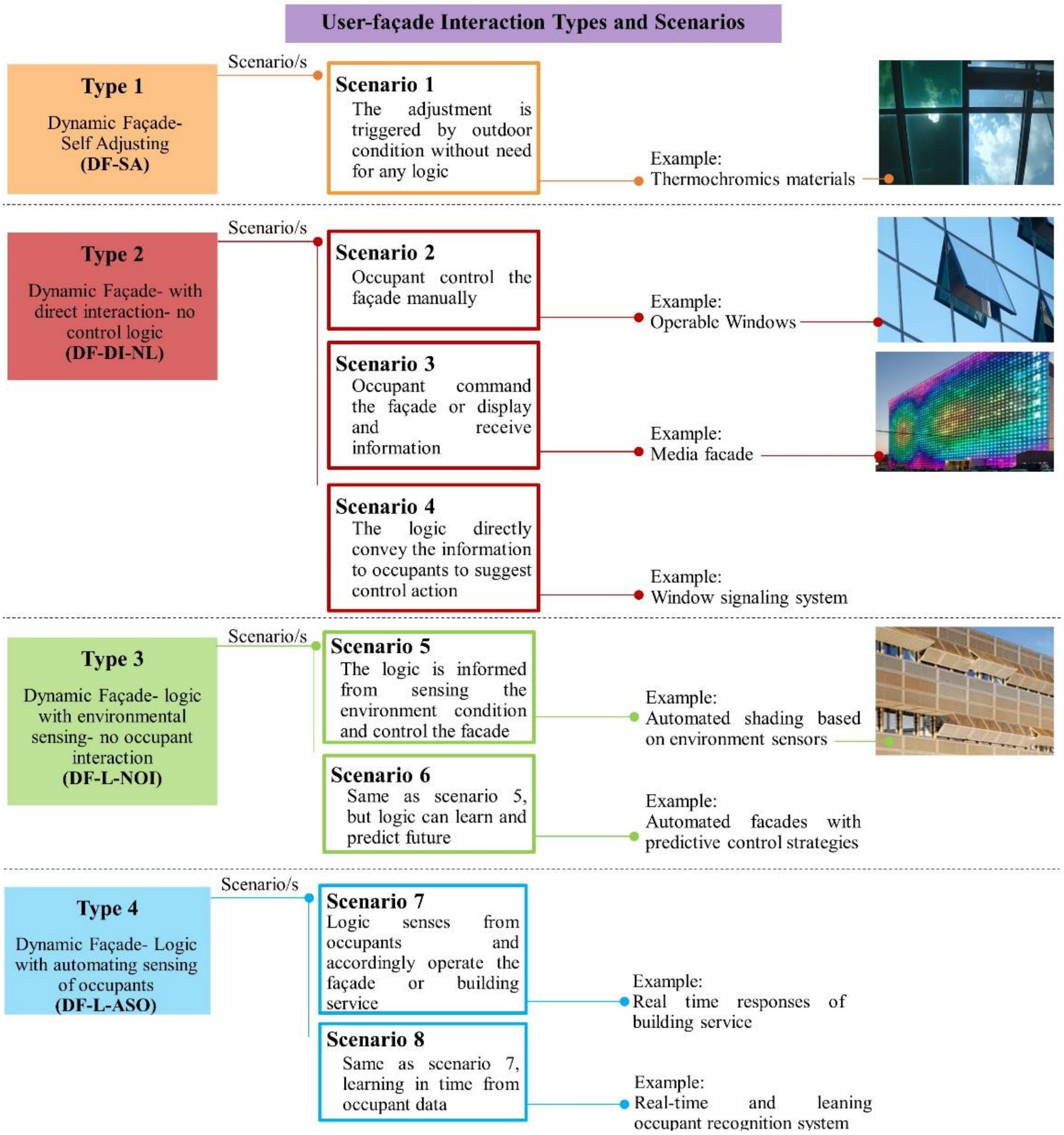

Figure 14: Interaction Diagram and Classification Scheme of Occupant Façade Interaction (Alessandra et al., 2020)

The four components mentioned above may have varied interactions with one another and external and interior environmental variables. In this way, they might develop various interactions. A variety of user-façade interaction scenarios may be created by combining the four major components, multiple interactions, and sensor logic. Different groupings can provide 13 alternative scenarios within the five primary Interaction categories. All five types and 13 scenarios were generated in the 2020 research by Alessandra et al. (Figure 15). As a result, this research is essential because it establishes a common basis for future studies on adaptable shells from the standpoint of the inhabitants. Based on their research, it will be feasible to explore the benefits and drawbacks of each interaction group, determine occupant satisfaction levels for each interaction type, identify environmental elements influencing user satisfaction.

The interaction types have been developed within five main classes (Alessandra et al., 2020):

- Dynamic Façade- Self Adjusting (DF-SA);
- Dynamic Façade- with direct interaction- no control logic (DF-DI-NL);
- Dynamic Façade- logic with environmental sensing- no occupant interaction (DF-L-NOI);
- Dynamic Façade- Logic with automating sensing of occupants (DF-L-NOI);
- Dynamic Façade- logic with direct occupant interaction (DF-L-DOI).

The following figure 15 summarises the possible interaction situations based on the classification method described in the preceding figure. The cornerstone for this thesis research will be the five primary scenarios and their sub-scenarios. Aside from understanding the technicalities of the CABS, the main focus of this study will be on the user-façade interaction types, as well as Post Occupancy Evaluation, in order to find the best interaction scenario from the users' perspective.



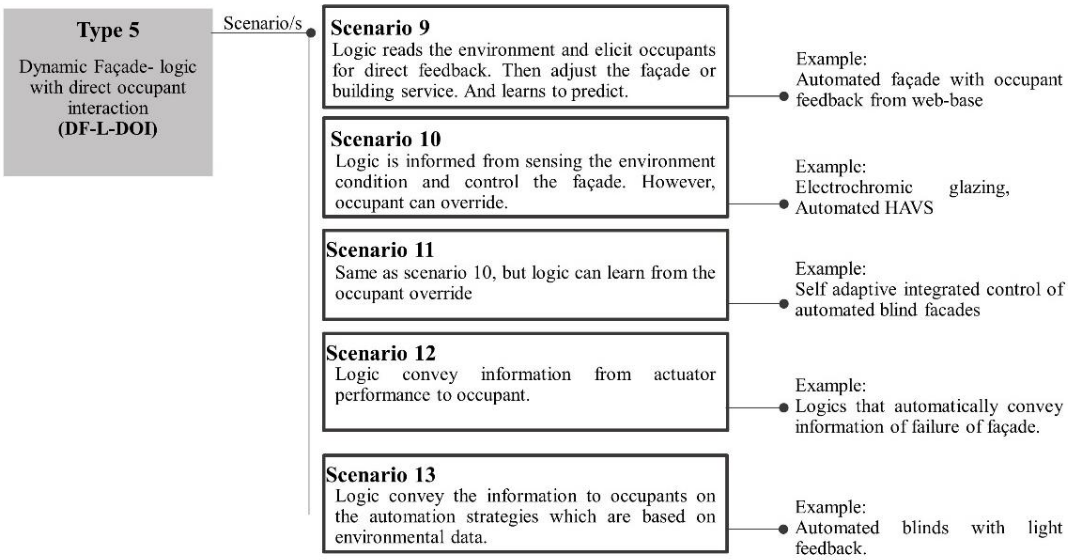



Figure 15: User Façade Interaction Types and Scenarios (Alessandra et al., 2020, amended by Author, 2021).

## 2.8 CABS Office Buildings Analysis Based on User-Façade Interaction Scenarios

As of the most recent CABS database update, there are 165 cased adaptable shells from all three groups of façade-systems, materials, and components. To choose the cases for this study, various constraints were imposed. The first limitation was the group type of shells, so “façade systems” were chosen. As a result, the focus of this thesis is on the designed façade systems rather than materials and components—the second limitation imposed on the buildings’ operation. As discussed in-depth, the majority of CABS cases are office buildings; hence, this research focuses on office buildings. Besides the selection of cases, this section carries a literature review to understand the intricacies of each system, and further research on user-façade interaction has been applied.

Two aspects were reviewed throughout section 2.8: a) user-centric studies, which led to an understanding of the importance of user-façade interaction in the complex relationship of users with CABS, and b) reviewing the CABS database, which resulted in an understanding of the CABS database classification.

As descriptive and comparative research, the case study part attempts to analyse many characteristics of CABS office buildings in macro-level contexts to introduce three CABS office building categories. First, after gathering all CABS office buildings from the database, selected buildings will be categorised based on the climatic zone in Phase I of the case study. This research aids in comprehending the essential shell detail used for each structure in a particular climate zone. Later in Phase II, the shell categories from Phase I will be combined with the User-Façade Interaction scenarios from previously. The functioning of façade systems was investigated throughout this study to allocate it to one or more user-façade interaction scenarios. Finally, in Phase III of the case study, the results of Phase II were combined with two more parts of "CABS typologies" and "Control Factors." The Phase III outcome is the introduction of a multi-domain taxonomy of CABS office buildings. Figure 16 depicts the organisation of a case study. All of the aforementioned phases are covered in the sections that follow.

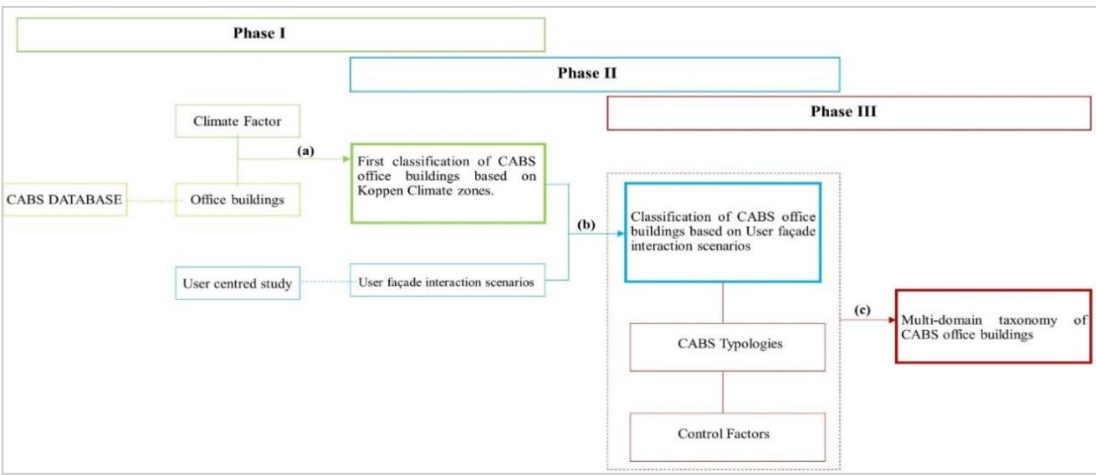


Figure 16: Phases of developing multidomain taxonomy of CABS(Author, 2021)

### 2.8.1 Phase I- Classification of the Cases Based on Koppen Climate Zones

By filtering the CABS database according to the specified limits, the cases were reduced to 24 office buildings with CABS façade-systems (detailed study of CABS office buildings presented in Appendix A). A locational analysis was performed as the first phase in the CABS office buildings case study. Twenty-four cases were entered to the internet website "batchgeo.com," and the cases' location is shown in Figure 17.

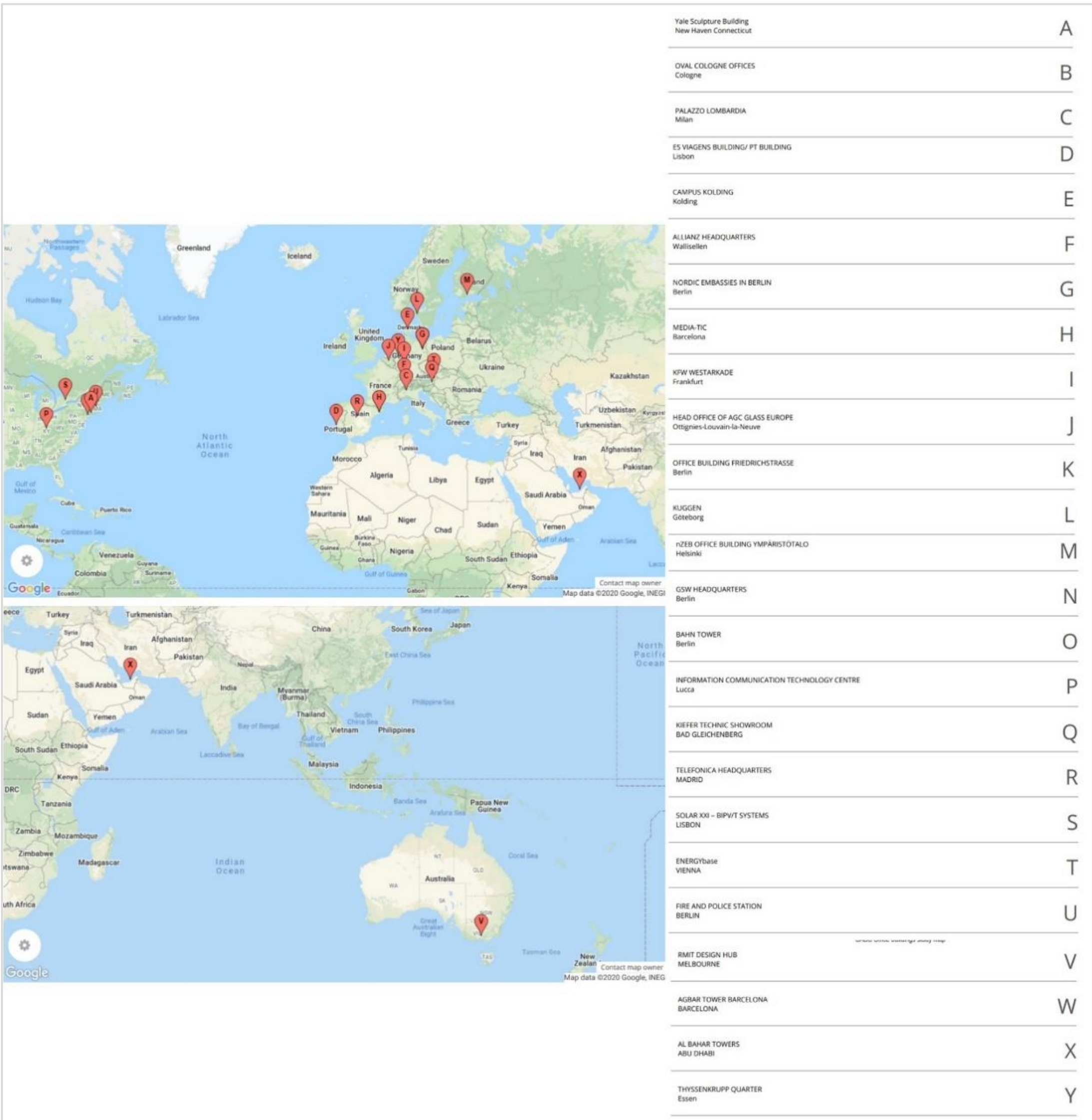



Figure 17: Location Map of the CABS Office Buildings (retrieved from https://batchgeo.com/map/cd08b547f0cb89143f81c38bfac2fc06)

The primary objective of doing a locational study is to determine the geographic distribution of cases in various climatic zones. Climate differences have an essential role in the design solutions provided by CABS. In this investigation, cases were categorised according to the Koppen Climate Zone Classification (Pernigotto and Gasparella, 2018, Almorox et al., 2015). The following Table 8 was created with the help of comprehensive literature research. This Table displays the selected cases grouped by climatic zone and features the primary façade elements of each case.

Table 8: Phase I- Façade details of CABS office building classified based on Koppen Climate Zones Classification (Aelenei et al., 2018, Pernigotto and Gasparella, 2018, amended by Author, 2021)

| **Koppen Climate Zone Classification** | | | **Building name** | **year** | **Location** | **Façade detail** |
|---|---|---|---|---|---|---|
| Level 1 | Level 2 | Level 3 | | | | |
| **Arid (B)** | Desert (W) | Hot (h) | Al-Bahr Tower | 2012 | UAE-Abu Dhabi | Double-skin façade, Shading devices, Ptfe martials |
| | Steppe (S) | Cold (k) | Media-TIC | 2007 | Spain-Barcelona | Pneumatic façade and blinds, , ETFE |
| **Temperate (C)** | Dry Summer (s) | Hot summer (a) | Information Communication Technology Center | 2003 | Italy-Lucca | Double skin façade, smart façade, Photovoltaic Panels (PV) |
| | | | Es Viagens building | 1998 | Portugal-Lisbon | Double skin façade, automatic venetian blinds, exhaust air-gap ventilation |
| | | | Solar XXI-BIPV/T system | 2006 | Portugal-Lisbon | Automatic vertical shutters |
| | | Warm summer (b) | Telefonica headquarter | 2008 | Spain-Madrid | Double skin façade, shading devices. |
| | Without dry season (f) | Hot summer (a) | Palazzo Lombardia | 2010 | Italy-Milan | Building integrated photovoltaic, renewable energy. |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Warm summer (b) | Head office of AGC Glass Europe | 2014 | Belgium-Ottignies Louvain la Neuve | Glass building, movable louvers, automated control, natural lighting |
| | | | Campus Kolding | 2014 | Denmark-Kolding | Shading device, energy saving, |
| | | | Oval Cologne Office | 2010 | Germany-Cologne | Automatic vertical shutter, OVAL, color in architecture |
| | | | Thyssenkrupp quarter | 2010 | Germany-Essen | Double skin façade. Smart envelope. Steel sheets. Energy saving/ |
| | | | KFW westarkade | 2010 | Germany-Frankfurt | Double skin façade, low-energy building, ventilation flaps |
| | | Cold summer (c) | Rmit Design Hub | 2012 | Australia-Melbourn e | Sunscreen, bipv, evaporative cooling |
| | | | Agbar tower | 2004 | Spain-Barcelona | Double skin façade, glass louvers |
| **Cold (D)** | Dry winter (w) | Warm summer (b) | ENERGYbase | 2008 | Austria-Vienna | Passive house standards. Double skin façade, shading devices, stepped façade. |
| | Without dry season (f) | Hot summer (a) | GSW Headquarter | 1999 | Germany-Berlin | Double skin façade, solar chimney, natural lighting, louver system. |
| | | Warm summer (b) | Kiefer technic showroom | 2007 | Austria-Bad gleichenber g | Double skin façade, shading device |
| | | | NZEB office building Ymparistotalo | 2011 | Finland-Helsinki | NZEB, integrated PV, double skin façade, solar shading. |
| | | | Nordic Embassies Berlin | 1999 | Germany-Berlin | Pre-patinated lamellas, sun shading, unified appearance |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | Fire and police station | 2004 | Germany-Berlin | Double skin façade, shading device, glass shingles. |
| | | | Office building Friedrichstrasse | 2011 | Germany Berlin | Rollers, high-performance façade, operable textile screens, double skin façade |
| | | | Allianz Headquarter | 2014 | Switzerland wallisellen | Curtain wall, shading devices, daylighting control. |
| | | Very cold winter (d) | Yale Sculpture building | 2007 | USA- New heaven Connecticut | Double skin façade, PV system, smart envelope |
| | | | Kuggen | 2011 | Sweden-Goteborg | Double skin façade, PV system, smart envelope. |

### 2.8.2 Phase II- CABS Office Buildings and User-Façade Interaction Scenarios

The selected 24 office buildings in the above table were thoroughly investigated from a technical and economic standpoint by COST Action TU1403-WG 1 (Smith et al., 2001). However, in the case study conducted by the indicated team, user-centric research is lacking. Furthermore, because of the current gap in the literature, any inquiry on CABS cases from the standpoint of user-façade interaction (in general, user-centric research) is strongly suggested. As a result, this study attempts to fill this gap in case studies of CABS office buildings. As an outcome, Alessandra et al.'s user-façade interaction categorization, published in 2020, has been combined with chosen buildings. This convergence adds a new part to the COST Action TU1403-WG 1 case study.

The Table 9 below presents a functioning description of the façade for each CABS office building. Based on a knowledge of their working mechanism, they have been grouped into distinct types and scenarios of user-façade interaction. In addition, a research map was created using batchgeo.com which is a same platform used by COST Action TU1403 research group (figure 18) that shows the location of each office building as well as the user-façade interaction categorization. This map will make it extremely easy to select cases based on interaction types, which will be helpful for future research in this subject.

Table 9: Analysis of CABS office buildings based on user-façade interaction scenarios (Author, 2021)

| # | Building name | Description of façade system | User-Façade Interaction Classifications | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | DF-SA | DF-DI-NL | | | DF-L-NOI | | DF-L-ASO | | DF-L-DOI | | | | |
| | | | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 | S11 | S12 | S13 |
| 1 | Al-Bahar Towers | Double skin facade. Umbrella-like shading devices that open and close according to the sun path. Controlled by BMS (Attia, 2017) | | | | | x | | | | | | | | |
| 2 | MEDIA-TIC | ETFE cladding: solar protection. Controlling the lighting and temperature. The first layer is transparent. The second and third are pattern designs. This system responds automatically through the triggering of a temperature sensor (Enric Ruiz-Geli, 2011) | | | | | x | | | | | | | | |
| 3 | Information Communication Technology Centre | Shading devices: the south façade is covered with semitransparent PV panels. Low-E glazing. Mobile transparent and opaque sections based on smart development (Sala and Romano, 2011) | x | | | | | | | | | | | | |
| 4 | Es Viagens Building/ Pt Building | Double skin façade. The air gap ventilation works automatically. *Horizontal shading venetian blinds. The occupants usually override these automatic shading controls (Marques, et al, 2008) | | | | | | | | | | x | | | |
| 5 | Solar XXI – BIPV/T Systems | Passive technologies. Designed with PV panels (Gonçalves and Cabrito, 2006) | x | | | | | | | | | | | | |
| 6 | Telefonica Headquarters | Special Glazing. Double skin. Glass fins. The façade results in the interaction of two systems, mutant glass and serialized shadows (arup, n.d.) | x | | | | | | | | | | | | |
| 7 | Palazzo Lombardia | Double skin façade. Photovoltaic panels integration. Shading protection devices. Sun shield layout (Regione Lombardia, 2017) | | | | | x | | | | | | | | |

| # | Building name | Description of façade system | User-Façade Interaction Classifications | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | DF-SA | DF-DI-NL | | | DF-L-NOI | | DF-L-ASO | | DF-L-DOI | | | | |
| | | | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 | S11 | S12 | S13 |
| 8 | Head Office Of AGC Glass Europe | Glass shading devices. Removable wooden shading elements (Attia and Bashandy, 2016) | | x | x | | | | | | | | | | |
| 9 | Campus Kolding | Applied 1600 triangular shaped steel shading devices. Automatic system. *Solar cells and mechanical low energy (Henning Larcen, n.d.) | | | | | x | | | | | | | | |
| 10 | Oval Cologne Offices | Wide glass façade following the sun path. Colorful glass folding sunscreens (Ruhmann, et al, 2012) | | | | | x | | | | | | | | |
| 11 | Thyssenkrupp Quarter | Steel sheets cladding. Vertical metallic shading devices. Automatically follow the sun path (Chaxi and Morel association, n.d.) | | | | | x | | | | | | | | |
| 12 | KFW Westarkade | Double skin façade. Zigzagging transparent panels and ventilation flaps cladding. Flaps are sensor controlled (Detail Inspiration, n.d.) | | | | | | | | | | x | | | |
| 13 | Rmit Design Hub | The shading device follows the sun path based on a computer-automated system (Designboom, 2013) | | | | | | | | | | x | | | |
| 14 | Agbar Tower Barcelona | Double skin. Aluminum and movable glass shadings. Glass louvers (in 14 angles). Louvers operate based on sensors (Jean Nouvel, n.d.) | | | | | x | | | | | | | | |
| 15 | ENERGY base | Dazzle slats. The windows are located high so that daylight can penetrate the rooms (Vienna business agency, n.d.) | x | | | | | | | | | | | | |
| 16 | GSW Headquarters | Double skin façade. Vertical shadings (Building skins, n.d.) | | x | | | | | | | | | | | |

| # | Building name | Description of façade system | User-Façade Interaction Classifications | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | DF-SA | DF-DI-NL | | | DF-L-NOI | | DF-L-ASO | | DF-L-DOI | | | | |
| | | | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 | S11 | S12 | S13 |
| 17 | Kiefer Technic Showroom | 112 panels that are electrically movable in a group or individually. Three-dimensionality and dynamic facade. Provides the shading needed (Uys, 2016) | | x | x | | | | | | | | | | |
| 18 | NZEB Office Building Ympäristötalo | Double skin façade. Photovoltaic cells and solar protection. Operable windows in atrium (Energy cities, n.d.) | x | | | | | | | | | | | | |
| 19 | Nordic Embassies in Berlin | Installation of copper lamellas (adjustable in group or individual) The shading devices work through hydraulic control (Danish architecture centre, n.d.) | | | | | x | | | | | | | | |
| 20 | Fire And Police Station | Glass shingles. The shingles installed on the windows can be open due to requests. Shingles operated by BMS, but individuals can override the decisions ( Hutton, n.d.) | | x | | | | | | | | | | | |
| 21 | Office Building Friedrichstrasse 40 | Wide transparent façade. controlled with glass and textile and wood shading devices (Meinhold, 2011) | | | | | x | | | | | | | | |
| 22 | Allianz Headquarters | Double skin façade. Cavity mechanically ventilated. The aluminum shades for sun control. *Computer-controlled (BAUMANN, n.d.) | | | | | x | | | | | | | | |
| 23 | Yale Sculpture Building | Solar shading, triple glazed low-E vision, and operable windows. Operable windows help natural ventilation. Interior shadings increase occupants' control (Kierantimberlake, 2008) | x | x | | | | | | | | | | | |
| 24 | Kuggen | Facades extruding out and increasing in size up to the upper floor. The upper floors create shading for the lower floors. A rotating shading screen responsive to the sun path (archdaily, 2012) | | | | | x | | | | | | | | |

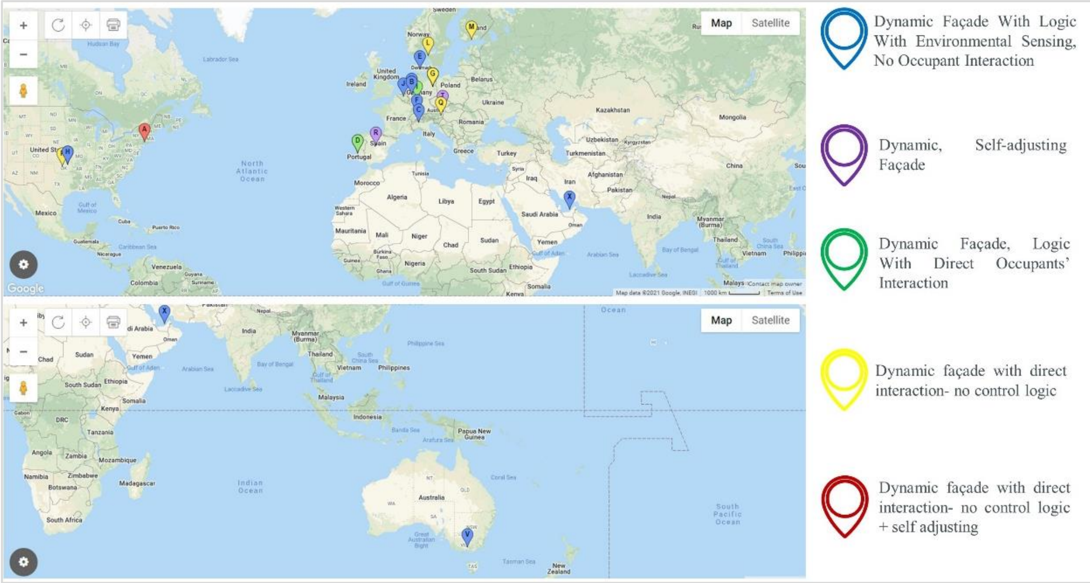



Figure 18: Location of CABS Office Buildings Based on the User-Façade Categories (retrieved from https://batchgeo.com/map/a7be91e654bf328a43b5eb0f7f2fd389)

The analysis of selected cases based on user-façade interaction types reveals examples generated within four major interaction types. Figure 19 depicts the analytical result from the preceding table. Based on this study, cases are almost evenly divided into two categories: 1) Dynamic Façade with Logic and Environmental Sensing, but no Occupant Interaction and 2) Dynamic Façade with Direct Interaction but no Control Logic. Surprisingly, the two groups listed above are fundamentally opposed regarding the occupants' engagement in controlling their working environment. In one scenario, occupants have no power over the façade performance, and logic controls everything; in the other interaction type, there is no logic and inhabitants, or building management are in command. Thus, for future research, comparing situations within these two categories to understand the occupants' satisfaction and productivity level can provide a viewpoint for determining the more suitable system from the occupants' perspective.

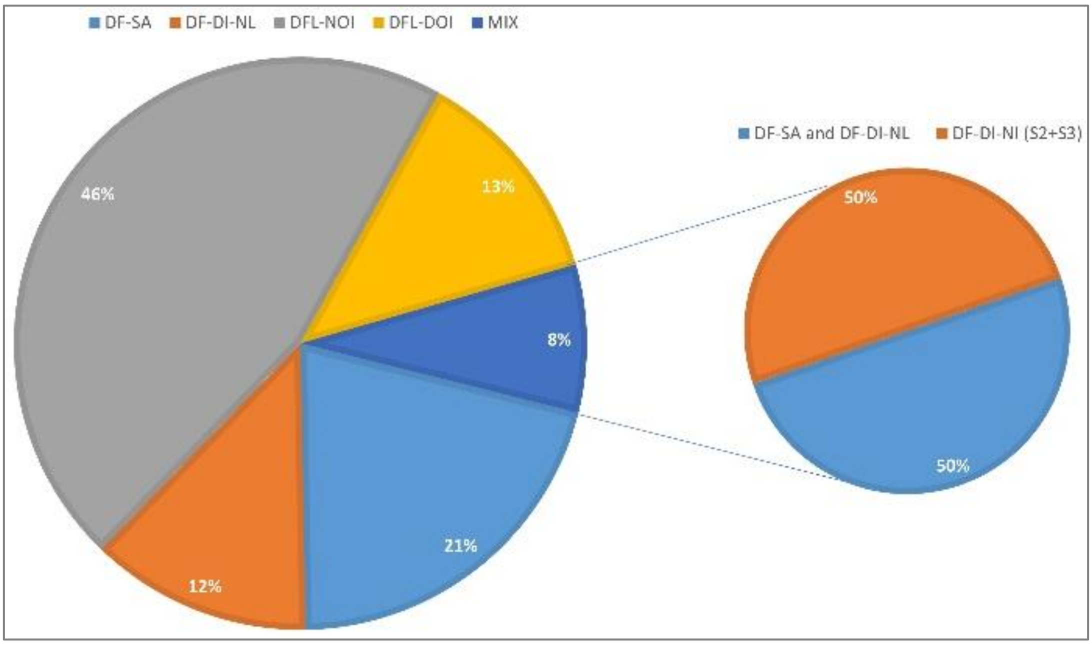


Figure 19: Number of Cases within Each User-Façade Interaction Type (Author, 2022)

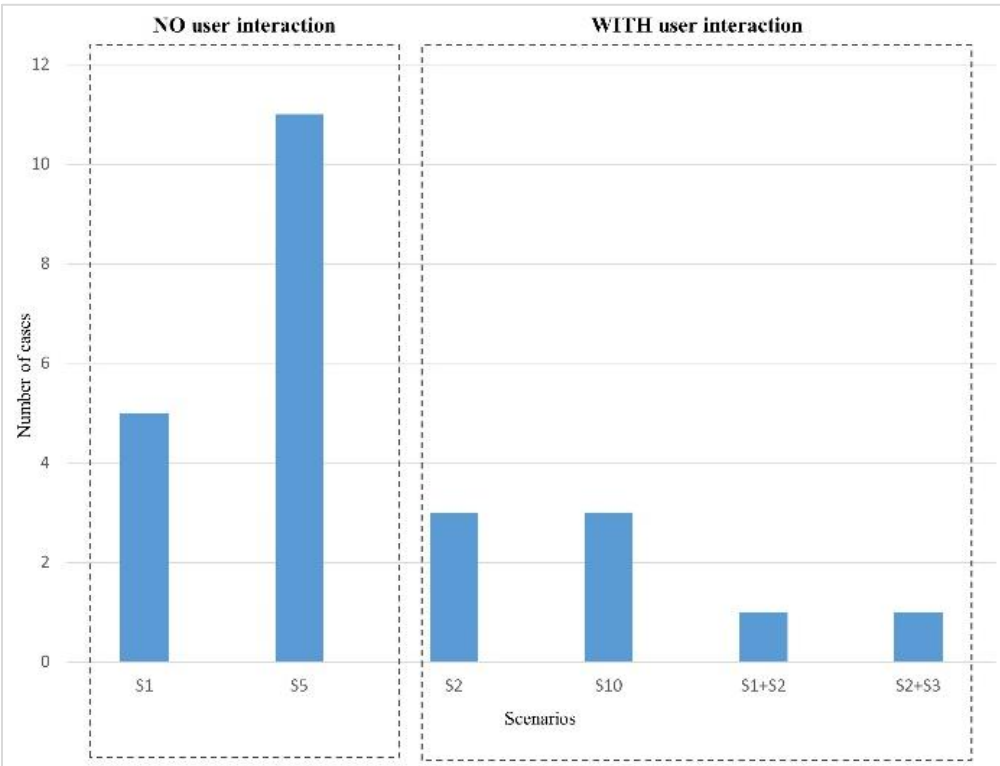


Figure 20: Number of Cases Per User-Façade Interaction Scenarios (Author, 2022)

Additional research can reveal new countenances connected to CABS office building façade systems and the creation of user-façade interaction scenarios (Figure 20). Case studies show that there has been no progress on interaction type 4, Dynamic Façade-Logic with automated sensing of occupants- (DF-L-ASO), for CABS office building façade systems to date. The absence of interaction type 4 emphasizes the lack of connection between logic and occupants in CABS office structures. The second result of the investigation on the selected CABS office buildings demonstrates a lack of progress in intelligent logic design. As shown in scenarios 5 and 10, produced scenarios based on logic are functioning with sensors that operate based on environmental variables. However, this logic has not progressed to the point where it can understand the inhabitants' behavior and requirements to foresee the future and respond appropriately. This research highlights the necessity for further improvement of the logic for CABS office buildings to boost tenant engagement in interaction situations (Table 10). Such advancements may be beneficial to occupant happiness and proactivity.

Table 10: Summary of case study based on user-façade interaction scenarios (Author, 2022)

| **Interaction Types** | **User-Façade Interaction** | **Scenario/s** | **Office Building** |
|---|---|---|---|
| DF-SA | NO | S1 | - Information communication technology centre<br>- Solar XXI-BIPV/T system<br>- Telefonica headquarters<br>- energy BASE<br>- NZEB office building Ymparistotalo |
| DF-DI-NL | YES | S2 | - Head office of AGC glass Europe<br>- GSW headquarter<br>- Fire and police station Berlin |
| | | S3 | NO DEVELOPMENT |
| | | S4 | NO DEVELOPMENT |
| DF-L-NOI | NO | S5 | - Al-bahr tower<br>- Media-tic<br>- Palazzo Lombardia<br>- Campus Kolding<br>- Oval Cologne office<br>- Thyssenkrupp quarter<br>- Agbar tower |

| | | | |
|---|---|---|---|
| | | | - Nordic embassies in berlin<br>- Ofiice building Friedrichstrasse 40<br>- Allianz headquarter<br>- Kuggen |
| | | S6 | NO DEVELOPMENT |
| DF-L-ASO | NO | S7 | NO DEVELOPMENT |
| | | S8 | NO DEVELOPMENT |
| DF-L-DOI | YES | S9 | NO DEVELOPMENT |
| | | S10 | - ES Viagens building/ pt building<br>- KFW Westarkade<br>- Rmit design hub |
| | | S11 | NO DEVELOPMENT |
| | | S12 | NO DEVELOPMENT |
| | | S13 | NO DEVELOPMENT |
| MIXED alternatives | YES | S1+S2 | - Yale Sculpture building |
| | | S2+S3 | - Kiefer Technic showroom |

### 2.8.3 Phase III- Introducing a New Taxonomy of CABS Office Buildings

The results of the user façade interaction research on CABS office buildings provide the option to move forward with a more comprehensive and multi-dimensional analysis. Thus, in Phase III of the case study, CABS office buildings were investigated using CABS typologies discussed earlier, control variables (thermal, visual, and acoustic), and interaction scenarios. This study section presents an innovative taxonomy for CABS office buildings based on a multi-disciplinary and multi-domain investigation. The categorization offered here can be applied in future multidisciplinary research on CABS office buildings. By covering many macro-level settings, such taxonomy might be advantageous for CABS investigations since it corresponds to the system's complexity (Figure 21).

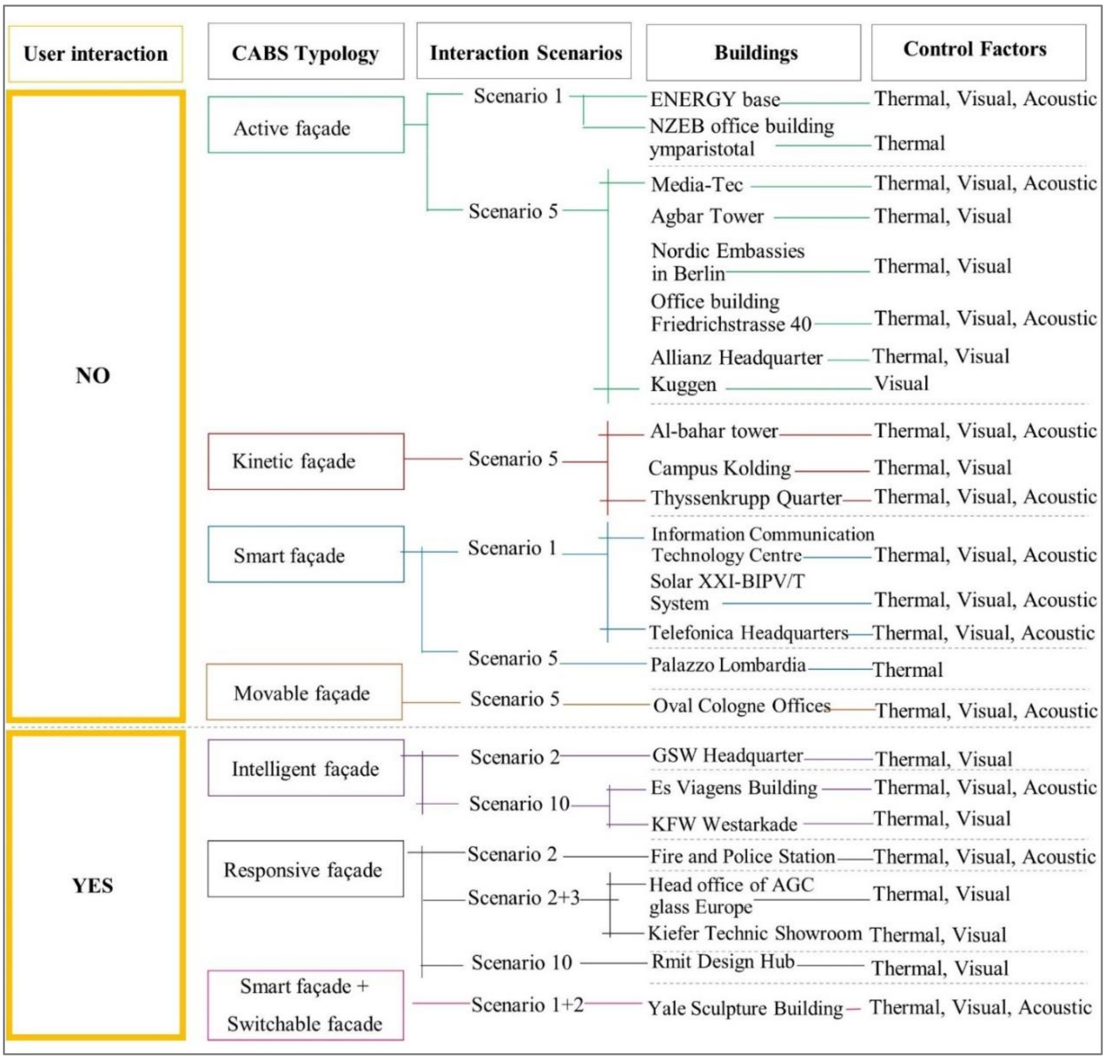



Figure 21: New Taxonomy of CABS Office Buildings Based on Multi-Domain Characteristics (Author, 2022)

## 2.9 Chapter Summary

This chapter attempted to provide a clear explanation of the CABS. As a result, a definition for this system based on the literature has been produced. After gaining a grasp of the system's performance benefits, all of its characteristics were researched in the literature. This study attempted to highlight the user-centric study concept after imagining a clear comprehension of the core keyword (CABS). First and foremost, the CABS literature has been presented, highlighting the absence of attention on user-centric research. The research of Alessandra et al., 2020 was chosen as the case study's foundation. In this regard, office building cases with CABS façade designs were decided and researched in three stages. During the analysis, examples were classified based on a) climate zones, b) types of user-façade interaction, and c) the introduction of a new taxonomy of CABS office buildings.

The key results reveal that most of the examples are built using macro-scale adaptability, closed-loop control, and thermal and optical physical domains. Developments for advanced logic systems in terms of user-façade interaction are pretty restricted. The majority of cases were built under two scenarios: a) Dynamic Façade with Logic and Environmental Sensing but no Occupant Interaction and b) Dynamic Façade with Direct Interaction but no Control Logic.

Aside from the detailed study over the CABS case databased described in this chapter, which led to the study adding new CABS taxonomy, the absence of occupant-centric studies on CABS, notably the POE and user satisfaction evaluation, is another focus of the chapter (Figure 22). In this context, in Chapter 3, Post Occupancy Evaluation, the other keyword of this thesis will be thoroughly examined. The following chapter pictures a better understanding of this concept, which helps develop a novel POE model in the last chapter.

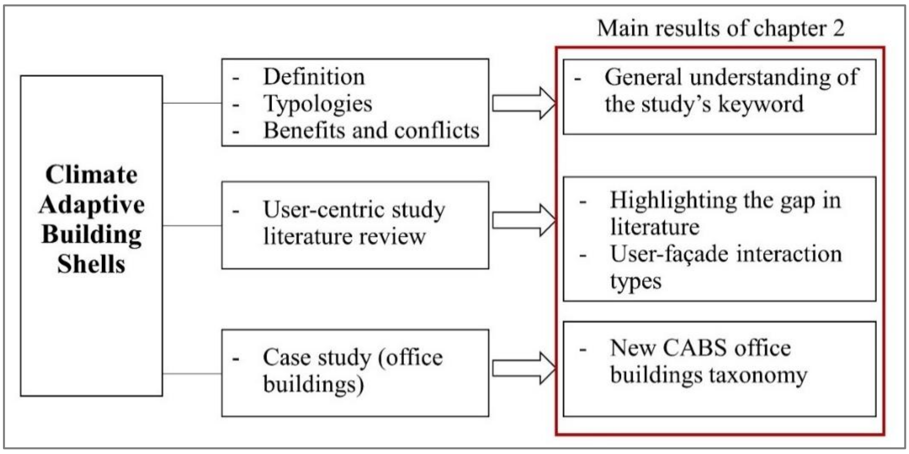


Figure 22: Summary of Chapter 2 (Author, 2022)

# Chapter 3

# POST OCCUPANCY EVALUATION

Whilst everyday products are tested and cross-checked, maintained and adapted for improved performance and consumer satisfaction, buildings, far more costly than vehicles, audio and other electronic equipment, are infrequently reviewed and appraised for essential improvements. This lack of examination and research is due to a variety of factors. Under these circumstances, each building stays a one-of-a-kind sample, design flaws are reproduced, and when a re-evaluation of the building as a final result is performed, it is frequently based on non-systematic troubleshooting. Enter Post Occupancy Evaluation (POE), a framework that helps thoroughly investigate buildings after being inhabited to gain lessons that will enhance their performance and future design (Jaunzens et al., 2002).

Plan analysis, monitoring of IEQ, IAQ, and thermal performance are among the methods used in POE, as are surveys like walk-throughs, observations, user satisfaction questionnaires, and structured interviews. POE researchers are frequently met with scepticism, if not hostility, because their work may create conflict between various stakeholders (including architect, client, investor, manager). As well as between these and the officials, exposing some to legal liability and others to potential demand for upgrade investments (Jaunzens et al., 2002).

This section of the thesis assesses building performance using Post-Occupancy Evaluation (POE). POE is a stage in the construction process that occurs after the planning, programming, design, construction, and habitation of a structure (Kantrowitz and Nordhaus, 1980) (Figure 23). This chapter attempted to give helpful information on the method and content of POE.

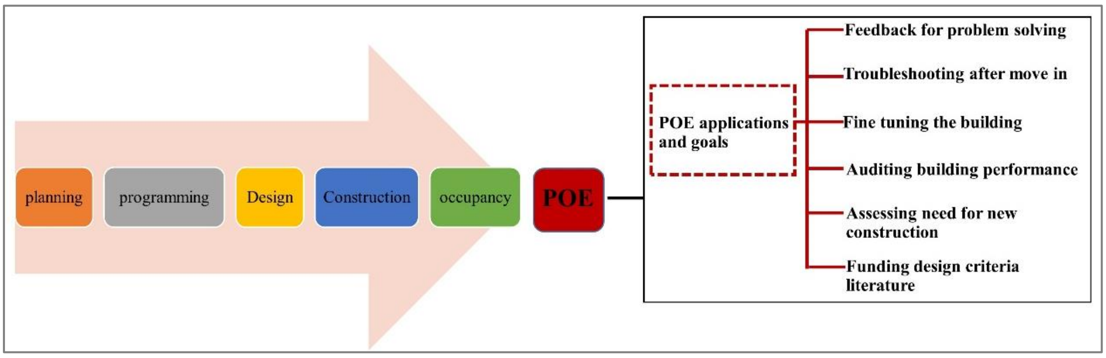



Figure 23: Process and Application Goals of POE (Kantrowitz and Nordhaus, 1980, amended by Author, 2021)

## 3.1 Definition of POE

POE is the practice of systematically and rigorously examining buildings after being constructed and inhabited for some time. POE focuses on building occupants and their demands, providing insights on the repercussions of previous design choices and the ensuing building performance. This understanding provides a solid foundation for future building design.

Building performance is reviewed regularly but not always self-consciously and explicitly. Conversations next door, for instance, in a hotel room may be overheard. The acoustic performance of the building is being evaluated in this situation. Reviews include the room temperature, lighting quality and even the esthetic quality of the view from the interior (Leaman, 2003).

An acceptable choice for users is the outcome of assessing the quality and functionality of a design. The designers' objective is to build products with desired characteristics that deliver excellent value while minimizing issues and errors. The purpose of POE is to compare the actual performance to specifically defined performance standards; the difference between the two is the assessment. According to the users ' aims and the time range concerned, POE has applications and advantages in the short, medium, and long term (Table 11).

Table 11: Post-occupancy evaluation benefits (Leaman, 2003).

| |
|---|
| **Short-term benefits** |
| • Identification of and solution to problem facilities<br>• Proactive facility management responsive to building user values<br>• Improved space utilization and feedback on building performance<br>• The improved attitude of building occupants through active involvement in the evaluation process<br>• Understanding of the performance implication of changes dictated by budget cuts<br>• Informed decision making and a better understanding of consequences of design |
| **Medium-term benefits** |
| • Built-in capability for facility adaptation to organizational change and growth over time, including recycling facilities into new uses.<br>• Significant cost savings in the building process and throughout the building life cycle.<br>• Accountability for building performance by design professionals and owners |
| **Long-term benefits** |
| • Long-term improvements in building performance<br>• Improvement of design databases, standards, criteria, and guidance literature<br>• Improvement measurement of building performance through quantification. |

## 3.2 Brief History of POE

The first substantial effort at POE occurred in the mid-1960s, when severe issues in institutions like psychiatric hospitals and prisons were recognized, some of which were related to the physical environment. The expansion of study on the interaction between users and building design may be seen in the 1960s (Preiser, 1995). Since the

1970s, several studies have focused on user satisfaction rather than the physical environment. Studies such as Oscar Newman's research on crime in high-rise public buildings might well be mentioned in this context. In this research, the author emphasized the link between the prevalence of crime and project size, scale, layout, etc.

Clare Cooper conducted another research in the 1970s. The author highlighted using survey interview and observation methodologies in POE data collecting in this work. By the end of the 1970s, initiatives were being undertaken to establish the field of POE. POE had evolved into a discipline by 1980. Three types of POE studies have been generated in this manner (Jaunzens et al., 2002, Leaman, 2003) (Figure 24). First, rigorous POE; all user groups and significant building aspects were investigated in this study. The second type of POE is based on social science, which provides a full view of the setting, consumer, contextual factors, design process, and cultural setting. Finally, individual POE indicates overall building performance, impacting building regulations, standards, and design approaches. The research on a Berkeley dormitory is one of the great examples. This research inspired a new generation of dormitories for public colleges (Jaunzens et al., 2002).

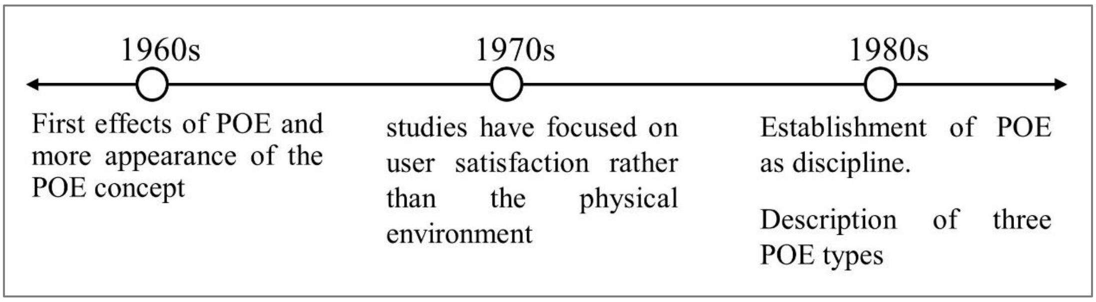



Figure 24: POE History Timeline (Leaman, 2003, Amended by Author 2021)

## 3.3 General Benefits and Barriers of POE

The underlying benefit of performing POEs is that important information is provided to assist the objective of continual development. Many decisions taken during the programming or design stages of building projects have historically been based on assumptions about how organizations work and how individuals utilize their spaces. A proper POE will give actual data to make choices, and accurate data is critical for informing and enhancing future projects (Hadjri and Crozier, 2009).

Standard practice in the facility delivery process, on the other hand, does not perceive the notion of continuous improvement or any ongoing engagement on the part of the designers as a barrier. The fact that designers are rarely compensated to go back and assess the consequences of their designs is evidence of this. POEs are not generally taught as part of traditional design education, which is one of the reasons they are not an embedded part of the normal facility delivery process. POE training work mostly as social designers or researchers. As a result, planning for POEs is not included in the standard procedure, and no time or funds is budgeted to accomplish such tasks (Hadjri and Crozier, 2009).

## 3.4 POE Characteristics

The foundations for the ongoing development in building procurement sought by the Higher Education sector are evaluation feedback. Effective feedback is an inherent aspect of good briefing and building design. Building performance review must occur throughout the building's lifespan to be most successful. POE is a method of delivering input throughout the lifespan of a building, from initial concept until occupation. Feedback may be utilized to guide future projects, whether it is about the delivery process or the technical functioning of the building. POE may be completed in seven steps. These phases are depicted in Figure 25 (Preiser, 1995, Preiser et al., 2015).

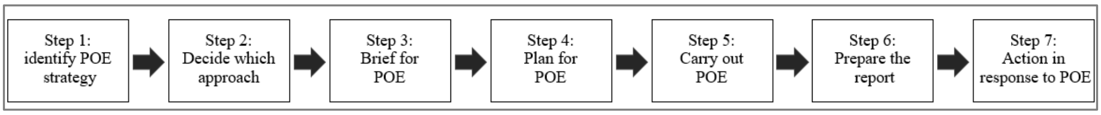



Figure 25: POE process overview (Preiser et al., 2015)

It is critical to understand the various aspects of a POE to construct a good POE based on the problem that has to be studied. These features are described in the subsections that follow.

### 3.4.1 Stages of Review

POE research attempts to answer a range of issues, such as 'does the building work as intended?' or 'have the users' needs changed?' This information is gathered through several methods such as questionnaires, focus groups, and data monitoring. Three steps of the review process were defined in the literature. As a reference, they are operational review (3 to 6 months after occupation), which can discover immediate concerns. Project review (12 to 18 months after occupation) can investigate the building's performance under the scope of scenarios. And strategic review (3 to 5 years after occupation) primarily verifies the building if it still meets the organizational requirements that may have been altered (Preiser et al., 2015).

### 3.4.2 Levels of POE

Three degrees of investigation may be defined: a rapid, surface assessment, a more in-depth investigative study, and a diagnostic evaluation comparing physical and occupant impressions.

An indicative review provides a high-level overview of the project. A few interviews are mixed with a walk-through of the building in a broad outlines technique. A brief sample questionnaire may also be distributed. The goal is to identify significant strengths and problems. The benefit of this is that it provides relevant information immediately and serves as the foundation for a more in-depth examination.

An investigative review is a more in-depth inquiry that employs more detailed research procedures to get more reliable facts. In this evaluation, various samples of people were given questionnaires, which were supplemented with focus group reviews and interviews to elicit further information on the problem indicated by the questionnaire results.

A broader diagnostic evaluation is a detailed examination that connects physical performance information to occupant reaction. The evaluator conducts an assessment of the building's environmental system in this form of review. Diagnostic evaluation in general covers energy consumption, $CO_2$ emissions, and acoustic performance of the building (Preiser et al., 2015, Jaunzens et al., 2001).

### 3.4.3 Elements of Evaluation

The applicability of POE strategies is determined by what is to be examined, the degree of information required, and the timing of the assessment. POE's attention may be divided into the process, functional performance, and technical performance. The following sections will go through all three of the previously stated areas.

Process: there are two components to evaluate; first, the project's delivery from concept through handover, which looks at how the project was completed and conclusions were drawn. The second, operational management, enquires of staff about building management (Zimring and Reizenstein, 1980). Functional performance; This relates to how effectively the building promotes the institution's organizational aims and objectives and how well individuals' demands are met. Technical performance; This entails assessing how the physical system performs, such as lighting, energy consumption, ventilation, and acoustics (Bordass et al., 2006) (Table 12).

Table 12: POE elements of evaluation (Bordass, et al., 2006).

| | |
|---|---|
| **Process** | |
| **Brief** | The way the team developed the brief on which the design was based, including financial management aspects. |
| **Procurement** | The way the team selection, contractual and technical processes were undertaken included time and value aspects. |
| **Design** | The way the team developed and refined the design included space planning, engineering, and financial management aspects. |
| **Construction** | The way the final commissioning of the building was managed, including financial and change management processes. |
| **Commissioning process** | The way the final commissioning of the building was managed, including final adjustments and the provision of documentation. |
| **Occupation** | The way the handover process was managed included rectifying last-minute snags and the removal/ relocation process. |
| **Functional Performance** | |
| **Strategic value** | Achievement of original business objectives |
| **Aesthetics and image** | Harmonious, neutral, iconic, influential, bland |
| **Space** | Size, relationships, adaptability |
| **Comfort** | Environmental aspects: lighting, temperature, ventilation, noise, user control |
| **Amenity** | Services and equipment: completeness, capacity, positioning |
| **Serviceability** | Cleaning, routine maintenance, security, essential changes |
| **Operational cost** | Energy cost, water and waste, leases, cleaning, insurances |
| **Technical Performance** | |
| **Physical systems** | Lighting, heating, ventilation, acoustics |
| **Environmental systems** | Energy consumption, water consumption, co$^2$ output |
| **Adaptability** | Ability to accommodate change |
| **Durability** | Robustness need for extensive routine maintenance, the incidence of "downtime" for unplanned technical reasons. |

### 3.4.4 Approaches and Methodologies

In general, there are two methodologies and primary options for conducting the POE: utilizing established methods or inventing a strategy based on current evaluation procedures (bespoke methods). A customised solution may be effective for specialized solutions, such as analyzing particular challenges (Preiser et al., 2015).

Each of the techniques and methods has advantages and limitations. It is feasible to state that the benefits of using established methods have previously been tried, are ready to use, and are supported by thorough research. However, they may not be appropriate for a specific context (summary of established methods are presented in Table 13). On the contrary, customised methods may be tailored to individuals' demands and are under the researcher's control. As a downside, it should be noted that developing a technique takes time and experience, and it may cost more than known methods (Preiser et al., 2015).

Table 13: Current established POE methods (Attia et al., 2015, Preiser et al., 2015, Bordass et al., 2006)

| Method | Stage of Review | Level of Review | Element of Evaluation |
|---|---|---|---|
| **De Montfort method** | Project review | Investigative | Process<br>Technical performance |
| **Post-Occupancy Review of Building Engineering (PROBE)** | Project review<br>Strategic review | Diagnostic | Functional performance |
| **Building Use Studies (BUS)** | Project review<br>Strategic review | Indicative | Functional performance |
| **Construction Industry Council Design Quality Indicators (CIC DQIs)** | Operation review | Indicative | Functional performance |
| **Liking score** | Project review | Indicative | Functional performance |
| **Energy assessment** | Project review | Investigative | Technical Performance |
| **Center of Built Environment (CBE) Building Performance Evaluation (BPE) toolkit** | Project review | Investigative | Functional performance |

Any existing approaches can be joined together to make a customised strategy, or a new way based on the POE concept can be established. To establish a novel POE approach, the techniques and methods in which the POE is carried out should correspond to the review stage to meet the aim of the study. Figure 26 provides an overview of how a POE can be carried out depending on the POE characteristics.

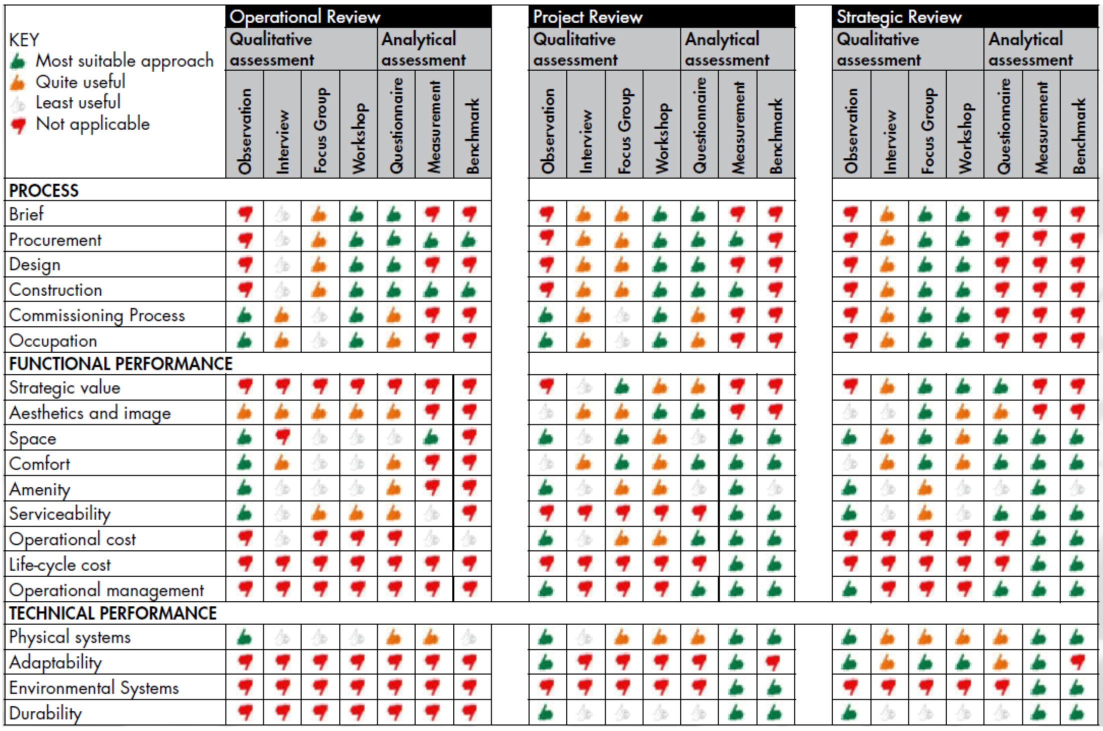


Figure 26: Check List for Established a Proper POE (Bordass et al., 2006).

## 3.5 Target of POE: Building Users

The nature and purpose of POE vary depending on who is questioned. Since each participant views the possibilities and risks of this tool and technique differently, the investor should have a personal interest in POE to assess design quality and prospective advantages - value for money spent – made possible by a superior end product, the building. However, in the face of such potential benefits, owners might not always want attention cast on the operation of their facilities. In extreme circumstances, they will be cautious of their legal guilt for malfunctioning or unsafe buildings. The building management should be concerned with reducing energy usage and maintenance costs. Knowing how the facility works by the occupants is an essential step in that direction (Nicol and Humphreys, 2002).

POE study on building occupants can differentiate between an emphasis on well-being and health and an emphasis on productivity (in the case of the building's manager or the institutional organization accountable for it) (the education system, etc.). These two themes are related, but in fact, there are conflicts of interest (Selkowitz, 2017).

The architect and consultants should strive to create the building feasible within the current economic, legislative, technological, and other restrictions. The duty of design professionals for the well-being of the people who use their facilities is a simple but often forgotten general concept, which is occasionally embodied in professional ethics standards and laws (Davara et al., 2006).

Institutional partners, including the many governmental agencies involved at the national and political levels, should be engaged in promoting improved design and building standards, such as those allowed by a continuous evaluation and upgrading process supported by POE. While each of these stakeholders approaches POE from a different, and at times disagreeing, perspective, it is clear that all have a chance to benefit from the ongoing implementation of POE practices, as well as the extensive use of these methods for recognizing flaws in current practices and producing solutions to correct them (Davara, et, al., 2006).

As occupant-centric research, the primary focus of this study will be on building users, and the suggested POE will be based on knowing the level of satisfaction and comfort of buildings’ users in buildings with CABS envelope systems. In this approach, the idea of comfort and several elements that affect user comforts, such as thermal, visual, IAQ, and acoustics, should be researched.

## 3.6 Defining the Study’s POE Variables

Following understanding POE's broad concept and features, it is necessary to establish the variable for each unique research to plan and model a POE. As a result, this study section demonstrates the POE factors for this research to develop a POE for CABS in the following chapters.

The approach for the review must be defined in the first phase. As previously stated, the review strategy relates to the period when POE will begin to be carried out following the occupation. Due to the CABS’ adaptability over the year, the building should be occupied for at least a year to obtain accurate data. The building and its residents were subjected to all potential seasonal circumstances in this scenario. As a result, the strategy review of this research is defined as a project review. After the building has been occupied for 12 to 18 months, the project is reviewed.

The level of POE must be defined in the next step; for this study, the POE must be implemented at the investigation review level so that an in-depth analysis may be performed. As the aspects of evaluation, the review should focus on functional performance. The notion of occupant comfort should be considered during the functional performance evaluation.

As a result, the study will focus on inhabitants and their comfort. However, before carrying out the functional performance to define what will be questioned, it is necessary to explore and evaluate the user's comfort, productivity, and distraction factors. Thus, the fourth chapter focuses on determining the criteria and standards of comfort to provide a broader view of what should be studied.

Finally, after defining all factors for designing a POE, the technique with which the POE should be carried out must be established. Because of the complexity and multi-domain properties of CABS transporting static and standard POE techniques cannot provide reliable data, as will be addressed more in the future chapters. Thus, in the last chapter of the research, chapter six, a new model for POE will be suggested based on the previously specified user-façade interaction scenarios, POE variables in this chapter, and comfort factors in the next chapter (Figure 27). With real-time data collection, adequate data storage, and the introduction of a questioner suitable with comfort settings, the suggested POE model may compete with the complexity of CABS. Based on the occupant-centric notion, this POE model can aid in decision-making.

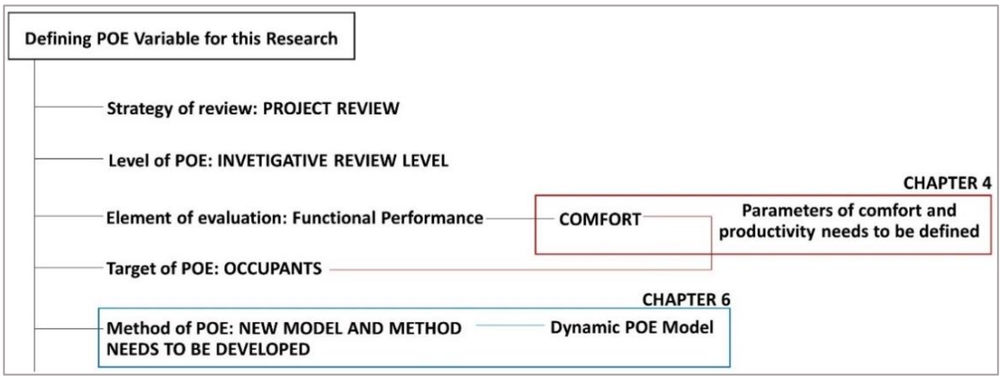


Figure 27: POE Variables for the Study (Author, 2021)

## 3.7 Chapter Summary

Chapter three attempted to go through the Post-Occupancy Evaluation method, first by describing the definition of this evaluation concept and then by analyzing its history and the processes of its progress until it arrived at the current stage. Following an awareness of the benefits and barriers of POE, the main section of this chapter attempted to describe the POE features that should be addressed while building the POE model and approach later in this study. The POE variables for this PhD thesis have been specified in the last section of the chapter. Defining variables demonstrates the necessity for more research into comfort factors and developing a suitable POE model with CABS complexity (Figure 28). The next chapter discusses the comfort factors used for questionnaire design later on. In addition, the new recommended model will be detailed in Chapter 6.

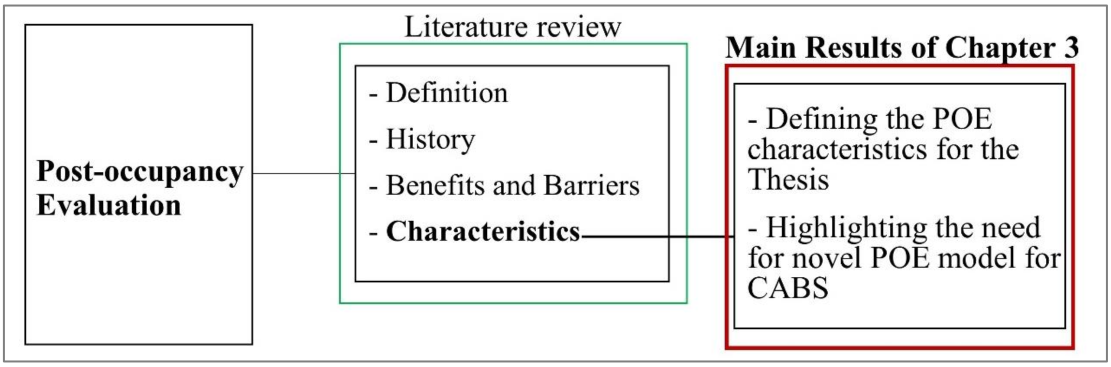



Figure 28: Summary of Chapter 3 (Author, 2022)

# Chapter 4

# COMFORT PARAMETERS FOR OCCUPANTS' SATISFACTION AND PRODUCTIVITY

Given both the existing buildings and the relatively high building projects rate, it is easy to see why all this focus has been laid on reducing the energy usage by the building industry through the implementation of the recommendations. Particularly in the last forty years, for resource efficiency, the use of renewable energy sources, and the incorporated, comprehensive design, construction, and maintenance of buildings (Papadopoulos, 2016).

However, in addition to the relevance of energy use, the fact that human beings devote 60–90 per cent of their lives to buildings must be recognized (Jantunen et al., 2011). Several literature review articles on building satisfaction and comfort have been issued over the decades. The bulk of those studies focused on thermal comfort and delivering frequent updates on improvements (Taleghani et al., 2013) (Cheng et al., 2012) (Rupp et al., 2015). Nevertheless, very few assessment studies have focused on post-occupancy evaluation and human comfort. Yet, scientific research effort in this subject is strong, with a wide range of applications, necessitating continuous monitoring advancements (Meir et al., 2007). The primary purpose of this phase of the study is to determine comfort metrics that will subsequently aid in constructing a post-occupancy evaluation model for CABS.

The absence of discomfort is stated as 'comfort.' Indeed, the term "comfort" can refer to a state of contentment, a state of cosines, or physical and mental richness. Circumstances based on various aspects are the basis of rationalizing comfort value in every place. The comfort of building occupants is hugely reliant on the many controls on multiple variables between them and their indoor settings (Nicol and Humphreys, 2002).

A building's occupants' comfort is affected by several elements. According to Frontczak and Wargocki's research, building design parameters, individual characteristics of occupants, and externally diverse climatic factors all have a significant impact on comfort reliability in terms of the underlying conditions of indoor spaces such as thermal, visual, and acoustic, particularly in interior environments (Frontczak and Wargocki, 2011).

Obtaining the best degree of comfort for the inhabitants necessitates the development of, at the very least, acceptable indoor environmental factors. Considering the multi-parametric aspect of comfort, it is necessary to analyze the Global Standards' criteria of acceptable values for the metrics and features of thermal, visual, and acoustic comfort and IAQ.

The international standards can be divided into three categories: a) International Standard ISO 7730, b) ASHRAE 55, and c) CEN 15251. The standards addressed in this research section are based on ASHRAE 55 International Standards. ASHRAE 55 establishes suitable conditions for a particular proportion of users and thermal comfort calculation procedures based on PMV/PPD.

## 4.1 Thermal Comfort

Thermal comfort refers to a person's positive sense of the thermal environment. It is described as various situations in which most individuals are at ease. Based on a study of several types of research, thermal comfort is ranked as one of the essential criteria for boosting occupant comfort and contentment with their interior environment.

Thermal comfort is defined by ASHRAE STANDARD 55-2010 as a state of mind that expresses satisfaction in thermal conditions. In greater depth, the inhabitants' happiness with the operating temperatures of a specific environment is assessed using a qualitative interpretation of a comfortable thermal environment (Dahlan, 2009).

Thermal comfort is achieved by a series of deliberate interactions between three personal and environmental factors:

- Physiological: how our bodies interact and communicate with our environment;
- Physical: the main criteria of our environment (temperature, humidity, air movement);
- Socio-Psychological: how we feel overall (tiredness, happiness, etc.) and the living social environment.

The physiological component: our bodies' compliance processes constantly aim to maintain our thermal exchanges with the environment by accelerating or slowing our heartbeat to adjust our blood flow and govern uniform heating. For example, shivering once too cold to boost heat generation and sweating extra when too hot to decrease surface temperatures through vaporisation. A pleasant interior atmosphere reduces the workload required by our bodies to maintain body temperature, resulting in a favourable energy balance (Fabbri, 2015).

In the physical aspect; Thermal energy is transported in the physical environment via conduction, radiation, and convection.  Conduction is energy transmission through a solid, such as a floor or wall. Convection transfers energy from a solid to a nearby gas or fluid. On the other hand, radiation is the energy released by a surface, such as a radiator.

The sociopsychological element; An individual's present emotional state, mood, degree of exhaustion, and so on, will all influence their experience of a place. Type of reaction how an individual perceives the physical world: one would anticipate a beach to be hot and a mountain lodge to be cold, but perceptions are more likely to be based on one's temperature profile. Other ambient elements, such as noise or light, may alter thermal perception, resulting in an increased sense of overheating (Fabbri, 2015).

In general, thermal comfort governed by environmental and human variables can be divided into the following categories: The former include (a) air temperature, (b) radiant temperature, (c) air velocity, and (d) humidity, whereas the latter include (e) clothing insulation and (f) metabolic rate (Parsons, 2000). Because each person has a unique thermal perception, it isn't easy to satisfy all users simultaneously. As a result, personal aspects are not considered, but a degree of flexibility should be allowed to change the interior conditions based on personal preferences.

### 4.1.1 Thermal Comfort Parameters

It is difficult to determine a single significant criterion for evaluating human comfort. As previously said, thermal comfort may be disclosed through six characteristics distinguished by individuals and environmental conditions. This study focuses on environmental factors, and individual parameters are beyond the scope of this study. Thus, the emphasis will be on four factors: air temperature, radiant temperature, air velocity, and humidity (Parsons, 2000).

#### 4.1.1.1 Air Temperature

The typical ambient temperature enclosing the occupant concerning place and time is the air temperature. As per the ASHRAE 55 guideline, the spatial estimate considers the ankle, waist, and head levels, which change depending on whether the person is seated or standing. The average is calculated using a three-minute duration with at least 18 evenly spaced data points. Because air temperature is measured with a dry-bulb thermometer, it is also known as dry-bulb temperature- ASHRAE Standard 55-2004- (Olesen and Brager, 2004).

#### 4.1.1.2 Radiant Temperature

The radiant temperature is proportional to the quantity of radiant heat conveyed from a surface. It is determined by the material's capacity to absorb or release heat, also known as its transmittance. The radiant temperature is determined by the temperatures and emission spectra of the surrounding medium. As well as the amount of the surface that the item "sees." As a result, the average radiant temperature felt by an individual in a space with sunshine flowing in varies depending (Halliday et al., 2003).

#### 4.1.1.3 Air Velocity

Airflow is known in HVAC as the air flow rate at a place without consideration to direction. As per ANSI/ASHRAE Standard 55, it is the average airspeed to which the individual is exposed concerning place and time. According to the standard effect temperature (SET) thermo-physiological model, the temporally mean is like the air temperature. In contrast, the spatial average is predicated on the notion that the body is subjected to constant airspeed. Nonetheless, certain places may have substantially non-uniform air velocity patterns and, as a result, skin thermal losses that cannot be termed uniform. As a result, the designer must determine the suitable averaging, particularly for airspeeds incidents on undressed body areas, which have a more substantial cooling impact and the potential for local discomfort (ASHRAE, 2013).

#### 4.1.1.4 Relative Humidity

The proportion of the quantity of water vapour in the air to the amount of water vapour that the air could store at the specified pressure and temperature is known as relative humidity (RH). While the human body possesses excellent receptors beneath the skin for sensing heat and cold, RH is perceived passively. Perspiration is an efficient heat loss technique that is based on skin evaporation. However, with elevated RH, the air contains nearly its maximum amount of water vapor, reducing evaporation and heat loss. Arid conditions (RH 20-30%), in contrast, are similarly unpleasant because they influence the mucosal membranes. The suggested indoor humidity in air-conditioned buildings is 30-60% (Tanabe et al., 2002) (Fiala, 1998). However, new guidelines, including the adaptive model, enable lower and higher humidity levels, relying on the other aspects present in thermal comfort.

### 4.1.2 Thermal Comfort Standards- ASHRAE 55

With the rise of global warming and the worldwide desire to become more energy efficient in all aspects of society, including building ventilation, thermal comfort has been a fiercely disputed topic for many years. The ASHRAE 55 standard intends to specify the different configurations of indoor thermal environmental factors and individual characteristics that will generate the thermal state of the environment satisfactory to the large percentage of space inhabitants.

Thermal comfort is defined as "that state of mind that expresses satisfaction with the thermal environment" by ASHRAE 55. It is used mainly in the United States. Still, it is well known internationally as the guidelines for designing, installing, and experimenting with indoor areas and mechanisms authored in relation to other well-known worldwide standards such as ISO 7730. The ASHRAE 55 was initially published in 1966 and is revised every three to seven years, given current research, experiences, and suggestions from designers, producers, and users. The far more significant and most recent editions of the guideline are the modified versions of 2004, 2010, and 2017. The standard was mainly created to improve thermal comfort in environments where people are inactive (i.e., office work). It may, therefore, be used to encompass different sorts of interior spaces, barring severe circumstances. Four pillars support this standard:

- The six environmental and personal parameters considered are temperature, thermal radiation, humidity, airspeed, activity level (metabolic rate), and occupant clothing.
- These considerations must be taken into account to comply with ASHRAE 55.
- The thermal parameters that ASHRAE intends to attain are suited to healthy adult users up to 3K meters in altitude when occupancy time must exceed 15 minutes.
- This criterion does not consider the effects issues such as air-conditioning, acoustics, lighting, or pollution- ASHRAE 55-2010- (De Dear, 2011).

The 2010 update brought back SET as a method for assessing and establishing the cooling sensation of increased airspeeds and overall indoor air movement, made significant modifications to evidently clarify required basic standards in both design analysis and recordkeeping to meet specific criteria, and added a comprehensive satisfaction survey and POE as a method for assessing thermal comfort both preemptively and retroactively. The most recent 2017 ASHRAE 55 standard update contains a new feature that may account for changes in occupant thermal comfort caused by direct sun radiation -ASHRAE 55- 2017- (Roth, 2017).

Indoor thermal comfort may be estimated using a combination of the elements mentioned above, including air temperature, thermal radiation, humidity, airspeed, and human variables such as physical activity and. At an early point in the design phase, numerical approaches evolved as a typical model for estimating comfort levels that rely on the described earlier environment and human factors. SimScale (computer-aided engineering (CAE) software product based on cloud computing) generates thermal comfort variable outputs derived from empirical estimates in Predicted Mean Vote (PMV) and predicted percentage of dissatisfied (PPD) fields established by P.O. Fanger using the static model for thermal comfort. Sections 4 and 5 of ASHRAE 55 specify the criteria and circumstances that must be satisfied to fulfil the guideline. According to general standards, the benchmark must be implemented to the specific space being evaluated, the occupants, locations within that space, and any outlier occupants.

ASHRAE 55-2010 emphasizes the need of maintaining well-qualified or well-optimized thermal comfort in an interior setting when HVAC design professionals must be pushed to do so. As a result, the ASHRAE 55-2010 standard specifies a heat balancing model that takes into account the parameters that contribute to thermal feeling. Various needs for various structures such as commercial buildings, hospitals, hotels, dorms, schools, and households are specified and calculated in this framework.

The table below shows the recommended requirements for interior thermal comfort as established by the ASHRAE 55-2010 Standard (Table 14).

Table 14: ASHRAE 55-2010 Recommended- Required Indoor Design Parameters (De Dear, 2011).

| **Indoor Area** | **Summer Condition** | | **Winter Condition** | |
|---|---|---|---|---|
| | Temperature $^{o}$c | RH % | Temperature $^{o}$c | RH % |
| **Rooms** | 23 $^{o}$c - 24 $^{o}$c | 30%-35% | 23 $^{o}$c- 26 $^{o}$c | 50%- 60% |
| **Lobbies** | 20 $^{o}$c- 23 $^{o}$c | 30%-35% | 23 $^{o}$c- 26 $^{o}$c | 40%- 60% |
| **Meeting rooms** | 20 $^{o}$c- 23 $^{o}$c | 30%-35% | 23 $^{o}$c- 26 $^{o}$c | 40%- 60% |

## 4.2 Visual Comfort

Visual comfort is associated with the response to the quantity and intensity of light in any given environment at any given moment. Visual comfort is dependent on users' capacity to manage the light levels around us. Visual discomfort can be caused by both too little and too much light. Changes in light levels or extreme contrast, on the other hand, can create tension and weariness since the human eye is constantly adjusting to light levels. It can vary based on the following parameters: the period of exposure, the kind of light, the colour of the eye, and the person's age (Lemon, 2015).

Evaluating a visual environment involves examining three significant factors: light sources (artificial/natural), light dispersion within the area (colour, intensity), and perception. Researchers have recently begun to comprehend how light affects our bodies and minds. Light has an immediate impact on controlling several bodily activities, including sleep, mood, and attentiveness. The natural or artificial light generates propagating energy, of which only a restricted spectrum of frequencies, spanning from infrared to ultraviolet, is visible to the human eye as light. The quantity of electromagnetic energy that reaches the eye and the spectrum of this light impact how humans perceive light. Knowing further about light and how to regulate it is critical since light directly impacts human health and well-being and experiences and understanding of surroundings. Individuals' personal history and culture influence how they perceive light and visual situations. The ideal range of illuminance varies considerably based on age and culture. For example, desired light hues in Asia differ significantly from Europe's (Lemon, 2015).

Overall, visual comfort is characterized as a situation exposed by numerous characteristics such as the amount, homogeneity, orientation, and level of light, the proportion of contrasts, the absence or presence of glare, and the temperature of colour. The colour temperature relates to artificial illumination, which is beyond the scope of this research. These visual comfort characteristics are not constant, and various environmental and other circumstances can influence them (Lemon, 2015). The measurements and factors of visual comfort will be described briefly in the following sections.

### 4.2.1 Light Uniformity

The consistency of lights in an environment is referred to as light uniformity. It is critical to ensure light homogeneity to guarantee that everything in the space is evident. When discussing light uniformity in an area, the task area and near surroundings are considered. The necessity of keeping a sufficient degree of illumination cannot be overstated. People frequently overlook the computation and assessment of light homogeneity in a place. When the light uniformity for interior or outdoor lighting is indeed very low, it causes discomfort. The notion of light uniformity states unequivocally that lights provide the brightness of an area. When discussing light homogeneity, the proportion of minimum illumination is frequently emphasized.

There is a requirement for adequate illumination uniformity over the particular workplace, independent of whether direct or indirect lighting is employed.

Uniformity is calculated as the minimum to average illumination levels in a given region. It is a measurement of value for the total illuminance spread. In a working environment with a 0.60 ratio, individuals do not detect differing lumen output with their naked eyes and believe themselves to be in a well-lit setting. Increasing the ratio to 0.65 will provide even more homogeneity, making persons with impaired eyesight relatively comfortable. Lighting uniformity can be obtained once more through the use of sensors as well as other control devices. A high-quality dynamic lighting system will maintain optimal uniformity in changing conditions, such as during the day when sunlight is the primary light source. Therefore, the job of artificial light is to keep the required homogeneity by illuminating those rooms that are further distant from openings and other streams of sunlight, such as skylights (Park et al., 2012).

### 4.2.2 Glare

Glare is a visual feeling induced by an enormous and unregulated light. It might be debilitating or merely unpleasant. It is perceptual, and susceptibility to glare varies greatly. Due to ageing, older persons are frequently more susceptible to glare. Discomfort glare is the sense of irritation or even pain caused by incredibly bright sources. In contrast, incapacity glare is the loss of visibility followed by powerful light sources in the field of vision.

Glare develops due to the following conditions, according to the Illuminating Engineering Society (IES) (IESNA, 2000):

- A very high level of light in terms of quantity
- A strong contrast, a highly excessive range of luminance exist.

Glare is affected by the location of the building's residents, individual sensitivity in the eye's capacity to adjust to a brightness environment, and a broad array of luminance fluctuation. However, various architectural solutions can be used to avoid or regulate glare. Shading, in particular, is regarded as one of the most critical architectural methods for controlling glare in buildings (Carlucci et al., 2015).

### 4.2.3 Degree and Level of Light: Amount of Light

The precise quantity of light justifies the strong visibility for the inhabitants. Occupants achieve their irritation or comfort condition according to the amount of light. When the amount of light is either low or extremely high, the state of discomfort is reasonably common (Carlucci et al., 2015).

Brightness or light output measures the total amount of illumination emitted by a light source per unit of time, adjusted per the human eye's tolerance to wavelengths of light, studied as the luminous efficiency function. A regular 100-watt incandescent bulb provides around 1,500 – 1,700 lumens (Carlucci et al., 2015).

### 4.2.4 Importance of Natural Lighting

Daylighting uses natural light, whether dazzling sunshine or subdued overcast light, to fulfil the visual expectations of building inhabitants in the profession of design. Natural light should be used as the main component of daytime lighting. A visually and thermally comfortable environment should be created, and electric lighting efficiency gains should be maximized while peak energy consumption is minimized. Designers and experts have lauded daylighting for its numerous aesthetic and physiological advantages. Researchers at the Lighting Research Center (LRC) in Troy, New York, for instance, have shown that daylight settings boost occupant productivity and comfort while also providing the psychological and visual engagement required to regulate human circadian cycles (Michael and Heracleous, 2017).

Overall, existing data indicate that an effective daylighting design—one that takes glare and heat gains into account—is likely to boost occupants' satisfaction, mood, and productivity. "The strong foundation may be achieved by combining dynamic daylighting control measures, such as motorized blinds, with passive solutions, such as louvres." Nevertheless, sunshine cannot be the only light source in a building because its consistency varies according to time, season, location, etc. As a result, an appropriate blend of natural and artificial light is critical for estimating ideal visual comfort regarding light throughout the day and night (Andargie and Azar, 2019).

## 4.3 Acoustic Comfort

Acoustic comfort refers to the well-being and feelings of residents of a building or dwelling about the noise-producing transport, equipment, activity, etc. Delivering acoustic comfort entails limiting invading noise and maintaining resident contentment. According to studies, well-designed acoustic environments aid to boost focus and communication. Besides immediate hearing impairment, loud noise may be harmful to human health in other ways. Other adverse effects of noise exposure encompass cardiovascular disease, high blood pressure, headaches, hormonal changes, psychosomatic illnesses, sleep disorders, stress reactions, aggression, continual feelings of dissatisfaction, and decreased overall well-being (GSA, 2012).

Acoustic comfort is influenced by the level and type of sound in an environment. As a physiological element of acoustic comfort, the human ear is divided into three parts: the outer, middle, and inner ears, which receive, transmit, and perceive sound accordingly. The eardrum vibrates due to sound volume, and this motion is communicated to the inner ear, where nerves are activated. Regarding the physical aspect of acoustic comfort, sound is defined as the mechanical disruption of a substance, which might be gas, liquid, or solid. The difference in the size of pressure fluctuations distinguishes between loud and low sounds. The magnitude of an acoustical quantity is expressed in decibels (dB) due to the broad range of sound pressures to which human ears react. The sound frequency is given in Hertz (Hz), which is the degree of vibration cycles per second. A healthy human ear can detect a wide variety of frequencies.

The acceptability of any particular sound is determined by various elements, including the kind of facility, the sort of activity being conducted, and the inhabitants' social and cultural norms. The origins of the sound and the condition of the building envelope affect the quality of sound in any particular interior area, which includes:

- Exterior noise (nearby traffic, neighbours)
- Interior noise (music, phone conversations)
- Impact noise (footsteps)
- Sound vibrations through the structure
- Equipment noise (ventilation systems, electronic equipment, pipes, elevators) (Acoustic comfort, n.d).

The range of variables determines the impact of sound on a human. These include the sound's consistency and familiarity, controllability, personal attitudes and tolerances, knowledge about the sound's substance, and need. The loudness is not affected precisely by the degree of sound intensity. The instinctively sound pressures can be sensed at a higher degree as stronger tones in any particular ground or sound frequency. Nonetheless, if the sound frequency varies and the sound pressure stays static, the perceived sound grows and reduces non-linear volume (Grondzik et al., 2010). The spectrum of human vocal frequency is noticeably perceptible by the human ear.

## 4.4 Indoor Air Quality

The presence of contaminants (particulate matter, volatile organic compounds, inorganic compounds, etc.) in nonindustrial buildings' interior air is classified as IAQ. These contaminants are harmful to the human body. IAQ has been created as a study field to secure and prevent persons from the detrimental health consequences of pollution. According to World Health Organization (WHO) data, individuals in metropolitan areas devote around 90% of their time inside. 70% in their workplaces and 20% in their homes. As per Environmental Protection Agency (EPA) data, interior pollutants are 2–5 times higher than outside contaminants (Argunhan and Avci, 2018).

A variety of factors can lead to poor indoor air quality:

- Radon is produced as a byproduct of the breakdown of uranium in soil or rock; it can even be generated by construction materials such as granite.
- Mould grows due to excessive indoor moisture and is commonly seen in schools and business facilities.
- Volatile Organic Compounds (VOCs) can be generated by disinfectants, air fresheners, flooring material, furnishing, or biochemicals produced as gases from goods or activities.

- Carbon monoxide CO is produced by generators, poorly maintained boilers, vehicular emissions from adjacent idle automobiles, and other sources
- Vacuuming, fireplaces, cigarette smoking, and other activities may create dust particles.

On IAQ metrics, the EPA, ASHRAE and LEED (Leadership in Energy & Environmental Design) all concur. The most important criteria are presented in Table 15 (Baloch et al., 2020). To maintain needed IAQ standards, more than basic thermostats or a building management system that lacks sensor technologies is required to assess particular contaminants or adequate HVAC operation. Alternatively, building managers are increasingly using Internet of Things (IoT) sensors to detect the presence of specific pollutants such as CO, particulate matter, VOCs, humidity, radon, and others.

Table 15: Acceptable levels of indoor air pollutants (Vural, 2011).

| Pollutant | Acceptable Level | Reference - Standard |
|---|---|---|
| **Carbon Monoxide** | 60 mg/m$^3$ (50 ppm) for 30 min | Air Quality Guidelines for Europe-WHO (World Health Organization) 1987 |
| | 40 mg/m$^3$ (35 ppm) for 1 hour | NAAQS (US National Ambient Air Quality Standards) 1990 |
| | 10 mg/ m$^3$ (10 ppm) for 8 hour | TS (Turkish standards) 12281 |
| **Carbon Dioxide** | 500 ppm for 8 hour | ASHRAE 1982 |
| | <1800 mg/ m$^3$ | WHO 1987 |
| | <800 ppm | TS 12281 |
| **Nitrogen Dioxide** | 150 µg/ m$^3$ (0.08 ppm) for 1 hour | Air Quality Guidelines for Europe-WHO-1987 |
| | 400 µg/ m$^3$ (0.21 ppm) for 24 hour | |
| | 100 ppb for 1 hour | NAAQS 1990 |
| | <0.05 ppm | TS 12281 |
| **Sulfur Dioxide** | <0.5 mg/m$^3$ for short term exposure | WHO 1984 |

| | | |
|---|---|---|
| | 75 ppb for 1 hour | NAAQS 1990 |
| | 0.14 ppm for 24 hour | |
| **Formaldehyde** | 0.1 $mg/m^3$ (0.08 ppm) for 30 min | WHO 1987 |
| | 120 $\mu g/m^3$ continuous | ASHRAE 62 - 1999 |
| | 0.75 ppm for 8 hour | OSHA (U.S. Occupational Safety and Health Administration) |
| | 0.016 ppm | NIOSH (National Institute for Occupational Safety and Health) |
| | <0.065 ppm | TS 12281 |
| **Ozone** | 150-200 $\mu g/ m^3$ (0.076-0.1 ppm) for 1 hour | WHO 1987 |
| | 100-120 $\mu g/ m^3$ (0.05-0.06 ppm) for 8 hour | |
| | 0.05 ppm | ASHRAE 62 - 1999 |
| | 0.12 ppm for 1 hour | NAAQS 1990 |
| | 0.075 ppm (2008 std) for 8 hour | |
| | <0.12 $mg/cm^3$ | TS 12281 |
| **Radon** | 100 $Bq/ m^3$ for 1 year | WHO 1987 |
| **Particles** | PM10 – 150 $\mu g/ m^3$ for 24 hour<br>PM2.5 – 35 $\mu g/ m^3$for 24 hour | NAAQS 1990 |

## 4.5 Chapter Summary

All of the aforementioned comfort factors can influence and contribute to building inhabitants' satisfaction and productivity levels to varying degrees. The study of comfort parameters can provide the opportunity to define the characteristics to be questioned using the Post-Occupancy Evaluation approach to find the highest degree of satisfaction. The requirements for each metric have been described in this chapter; however, this research takes a more subjective approach to the issue and seeks to understand the occupant's feelings by focusing on the concept of occupant-centric study. However, comparing the inhabitants' feelings and the established requirements might provide other perspectives on the subject. The comfort variables outlined in this chapter will be implemented in Chapter 6 and developed model and questionnaire. Thus, understanding the comfort aspects, in general, has been critical for the further development of this study (Figure 29).

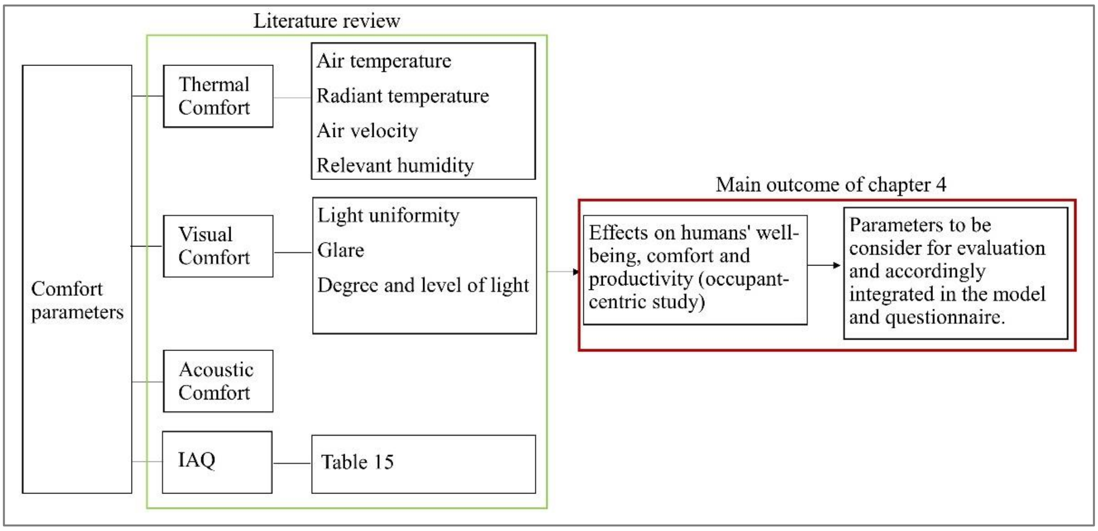


Figure 29: Summary of Chapter 4 (Author, 2022)

# Chapter 5

# REVIEW OF POE METHOD FOR CABS

As the world establishes and develops energy-efficient and advanced automated façades, it looks forward to optimizing the total work, living, and learning environment indoors. POE was historically used to review users' experiences in both outdoor and interior contexts. POE Demand for CABS has increased due to a growing desire to meet more ambitious environmental, social, and economic performance objectives (Brager et al., 2004). The usage of CABS necessitates a unique way to gather input on user experience and building performance in use. POE for CABS comprises researching occupant interactions with the envelope and entire building performance regarding energy consumption, IEQ, occupant satisfaction, well-being, and productivity (Loonen et al., 2013). Within this context, the primary focus of this study will be on user satisfaction and productivity.

As previously stated, there is a lack of comprehensive POE for CABS that delivers both qualitative and quantitative evaluation while also including users, designers, and building operators. Different assessments and evaluation methodologies are required for adaptable façades due to the CABS' adjustment to changing environmental conditions daily, seasonal, or annual basis. Because of their transitory and dynamic character, those façades are a unique construction technology with no precedence in systematic assessment frameworks and techniques (Attia, 2018).

As a result, this chapter has attempted to provide information on current research relevant to this issue. Reviewing the recent studies in this context will highlight the critical point for developing a novel POE model for CABS. Accordingly, in the other section of this chapter, based on the current studies on CABS, a survey based on occupant-centric focus has been developed.

## 5.1 Background of the Study

The assessment of CABS response to climate and occupant demands is crucial. CABS systems are distinguished by their dynamic flexibility and multi-usefulness of their components. Some of them take on specific tasks to improve thermal and visual comfort conditions. The impact of dynamic measures for thermal comfort, for instance, on user perception, necessitates objective criteria different from established comfort models (Bilir and Attia, 2018).

The dynamic nature of CABS necessitates ongoing or high-frequency data collection from occupants to acquire their reaction to transient changes in CABS parameters. CABS can have varying impacts on occupants relying on the starting and finishing states of the adaptive process.

POE for CABS evaluation is requested towards the end of the shell delivery procedure. The life span of Adaptive Shell (AS) is long, necessitating a continuous POE instead of an on-off POE, particular for the duration necessary to analyze the adaptation of the shell. Because of the characteristics of AS, POE must be altered to become transitory and regular to match control techniques, track occupant reaction behaviours and the AS response or activity. According to the findings of a CABS literature research (Bilir and Attia, 2018), there is a lack of comprehensive POE to provide for CABS and enable users while ensuring control by building operators throughout the AS's life cycle. This contradiction needs continual input and adaptable building management and control systems and software.

Nevertheless, with increased awareness of well-being and inhabitant input, including the proliferation of low-cost sensors and interaction equipment, a new strategy to managing this complicated challenge is required. The functioning of AS necessitates that users be prioritized and that a building management system (BMS) does more than just react to the operators. Hence the need to balance running the actuators on the façades and responding to human demands (Figure 30).

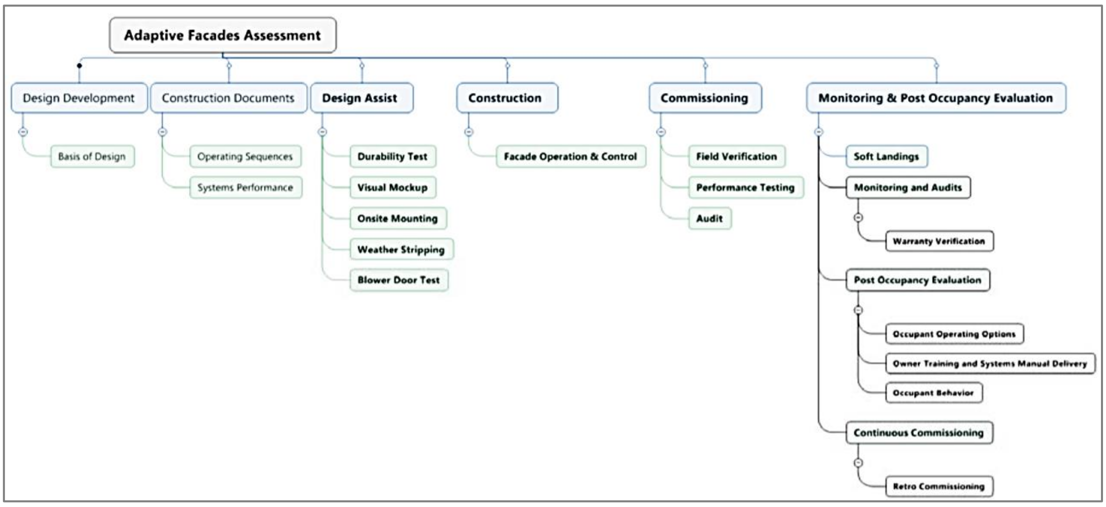


Figure 30: Adaptive Façade Assessment (Bilir and Attia, 2018)

### 5.1.1 Occupants' Behaviour Monitoring

POE is a process for conducting a systematic examination of buildings after they have been occupied with gaining lessons that will enhance their existing conditions and inform the design of future structures. Many dispersed advancements have been documented. However, till today, comprehensive research on monitoring the users behavior has not been presented. The ambiguity of occupant behaviour continues to be the most prevalent issue in the studied literature (Meir et al., 2009).

As per Brager et al., occupants with varying levels of direct control had significantly variable thermal reactions, even when exposed to identical thermal surroundings, clothes, and activity levels. In buildings with adaptive facades, occupant control is also determined to be the most crucial factor influencing occupant satisfaction. According to survey data, facade design significantly affects residents' perceived control over and satisfaction with their settings.

Simple quantitative occupant simulations must be used by facade architects, engineers, and management. In the lack of trustworthy models related to occupants, the judgment of the building design might be not accurate (O'Brien, 2013). Moreover, study on the practical efficacy of adjustable facades in real-world structures, as well as strategies for monitoring occupant behavior, is lacking.

### 5.1.2 Key Challenges of CABS Assessment

The performance evaluation of CABS before or after occupancy has problems since no technique satisfies the system's complexity, and all methodologies present limitations. The literature of case studies on CABS buildings, specifically for POE, is quite restricted, emphasising the need for a comprehensive POE model for CABS. This section of the study attempts to summarise prior case study research on this issue. Later, after outlining the limits of existing models, two critical studies for model development are reviewed that took a step ahead in enhancing the POE technique.

One of the first case studies on CABS, given by Attia and Bashandy in 2016, focused on the pre and post-occupation of AGC's Belgium headquarters. The study's goal was to present the building's design and construction process and its function in detail. Many elements, including thermal comfort, lighting quality, air quality, and noise, have been studied. However, as the authors have synthesised, the occupant comfort (POE research) must be assessed, and a full assessment is required.

Another Attia study published in 2017 featured a case study on the Al Bahr tower in the UAE. According to the study's author, there is a lack of established CABS evaluation techniques. The research aimed to give a detailed case study and analyse the selected building's pre and post-occupancy performance. From the POE standpoint, the study demonstrates a lack of concern for POE and underestimates the relationship of such a complicated shell with occupant satisfaction. The author suggests that greater attention should be paid to real-time data gathering to obtain more reliable statistics for occupant satisfaction. The mashrabiyas work differently within different time-spaces; thus, the occupants' perceptions might be varied.

Finally, Bilir and Attia published a case study of electrochromic (EC) glazing in 2018. As the authors point out, little research has been conducted on EC glazing performance. The primary goal of this research is to comprehend the CABS instance's performance and investigate thermal and visual comfort. Employers completed 39 surveys to carry the POE. According to the study, the lack of a heating system and control over the building shell create discomfort. However, the lighting quality level is at a comfortable level for users. However, the study was only conducted once, which may not provide accurate statistics because the building's performance varies over the year. Table 16 summarises the few case studies in this subject and the research synthesis linked to POE.

Table 16: CABS case studies and POE synthesis (Author, 2022)

| # | Publication | Author/s and Year | coverage | Review or case study | Main Goal | Main synthesis | Missing aspect |
|---|---|---|---|---|---|---|---|
| **1** | Patterns of occupant interaction with window blinds: A literature review (Wymelenberg, 2012) | Wymelenberg, 2012) | Only Windows | Case study | Presenting a POE study. | Users' satisfaction affecting by user s control in intelligent facades buildings | Not a multidisciplinary study compatible with CABS complexity |
| **2** | The contextual factors contributing to occupants' adaptive comfort behaviors in offices – A review and proposed modelling framework | O'Brien and Gunay, 2014 | Human behavior | Review | Presenting a framework for studying occupants' behaviour. | No synthesis about interaction effects on users' behaviour and satisfaction | User-façade interaction factor |
| **3** | User satisfaction and interaction with automated dynamic facades: A pilot study | Bakker et al., 2014 | Users' satisfaction | Case study | Investigating the user satisfaction in buildings with automated façade | Not considering the complexity of different CABS types.<br>Not considering user interaction with the façade | Not a multidisciplinary study compatible with CABS complexity |
| **4** | Evaluation of Adaptive Facades: The Case Study of AGC Headquarter in Belgium | Attia & Bashandy, 2016 | CABS | Case study | Presents in detail the design and construction process of the building plus its use | The occupant comfort (POE study) needs to be quantified, and a comprehensive assessment is needed | Human behavior and multidisciplinary study is missing |
| **5** | Review of current methods, opportunities, and challenges for in-situ monitoring to support occupant modelling in office spaces | Gilani and O'Brien, 2017 | Model | review | Reviewing the users' behaviour in the context of existing buildings | No synthesis about satisfaction level.<br>Interaction effect on users | Not a multidisciplinary study compatible with CABS complexity |
| **6** | Evaluation of adaptive facades: The case study of Al Bahr Towers in the UAE | Attia, 2017 | CABS | Case study | Presents a detailed case study and evaluate the pre and post-occupancy | The lack of seriousness for POE.<br>Underestimating the relation of the shell with occupants' satisfaction. | Human behavior and multidisciplinary study is missing |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | performance of the selected building | | |
| **7** | Comprehensive analysis of the relationship between thermal comfort and building control research – A data-driven literature review | Park and Nagy, 2018 | Thermal comfort | Review | Reviewing two research fields of; optimal building operation (control) and users' thermal comfort. And studying their relation | Building controls focus on the building energy consumption rather than the thermal comfort of users.<br>Not a multi-discipline study. | Not a multidisciplinary study compatible with CABS complexity |
| **8** | A review of occupant-centric building control strategies to reduce building energy use | Naylor et al., 2018 | Energy | Review | Reviewing building control systems and advanced occupant-centric controls. | Suggest an optimum point balancing the complexity of a system against its potential for saving energy.<br>Not a multi-discipline study. | Not a multidisciplinary study compatible with CABS complexity. |
| **9** | Performance Evaluation of Adaptive Facades: A case study with electrochromic glazing | Bilir & Attia, 2018 | CABS | Case study | To understand the performance of this CABS case and study the thermal and visual comfort | There was an unexpected level of difficulty in assuring the POE in the building with EC glazing.<br>There is a need for independent studies on users' well-being and dynamic visual comfort for dynamic glazing. | Human behavior and multidisciplinary study is missing |
| **10** | Occupant-Façade interaction: a review and classification scheme | Luna-Navarro et al., 2020 | CABS | Review | A novel classification scheme is proposed for multidisciplinary research | No evaluation has been done.<br>Future research directions on occupant-façade interaction are identified | The study must be merged with other factors of human behavior |
| **11** | Test rooms to study human comfort in buildings: A review of controlled experiments and facilities | Pisello et al., 2021 | Comfort | Case study | Overview of single and multi-domain comfort experiments conducted in test rooms. | Similar studies must be done on the extended environment. | Study has been done in a small scale and isolated lab environment. |

Derived from the literature review, four significant problems or features of adaptable facades that cause their assessment difficulty may be identified:

- Novelty: presently, just a few recorded case studies contain data concerning the operational performance of buildings equipped with CABS. Many alternative concepts and technologies are present or in the works. With a tiny sample of CABS, making generalizations is skewed. Furthermore, each AF is unique, and benchmarking data is scarce. The majority of the façade systems are custom-made; façade engineers lack mature expertise in the design, installation, operation, and evaluation of CABS.
- Complexity and dynamism: Fixed indicators and measures such as U-value and g-value have been used to evaluate conventional or permanent façade components. In dynamic systems, static values and measurements have minimal importance. Afs are likewise multi-functional structures that frequently include many sub-systems. They are capable of performing numerous functions simultaneously. Performance evaluations were not designed to account for this complexity and dynamic. There are no monitoring mechanisms, and many modelling tools lack the ability to represent time-varying building envelope parameters (Loonen et al., 2014).
- Intelligence: The efficacy of the operation strategy impacts the performance of dynamic systems such as CABS. Because Afs are very climate and occupant sensitive, they are challenging to operate and regulate. Because of climatic variables, each façade treatment is particularly localized, responding uniquely to environmental conditions. CABS, by definition, rely on high-performance technology with great accuracy and reactivity. As a result, they are compassionate and local solutions.

- Unpredictability: It is unclear if the maintenance party can employ the design-phase simulation throughout running because it is uncertain and unstable. There are frequently operational discrepancies between design intent and reported performance which might be ascribed in part to the character of AF. Unlike HVAC system performance measurement, understanding how Afs operate is far more complicated. AF systems are frequently integrated with small-scale HVAC systems, and no backup mechanism is in place (Day and Gunderson, 2015).

## 5.2 Difficulties of Carrying POE for CABS

This section has carefully researched methodologies and approaches for carrying a POE evaluation. However, the concern is whether existing POE approaches are appropriate for analyzing CABS. Based on a literature review on POE techniques and their applicability for CABS evaluation in terms of user satisfaction and comfort, growing constraints inherent in current POE approaches may be identified. The following are some of their limitations:

- Existing POE approaches do not provide real-time data collection and momentary assessment, which are critical for documenting and validating CABS' dynamic performance and reactivity.
- Current approaches place a high value on occupant comfort concerning reaction and control. They are often unable to evaluate the user's engagement with the CABS in the short term.
- The current POE approaches do not pinpoint the source of discontent. They instead give a holistic analysis based on a quarterly or yearly review and therefore do not permit the capture of the consequences of CABS changes at a specific moment. Researchers and building specialists cannot link or separate

occupant interaction and behaviour from the general environmental effects of CABS or BMS.

- Most of the time, POE results are not sent back to the operator. The feedback loop is not circular but relatively linear. At the same time, there is an absence of continuous input, which would allow occupants to react to energy consumption or comfort enhancement initiatives throughout operating hours. Completing the data loop is also critical for enabling dynamic POE, which is required to educate and alter CABS control techniques to match or forecast real occupant needs.
- Researchers and construction specialists lack a standard for comparing AF to the typical POE of buildings databases. Most POEs are substantially tailored to better monitor building behaviour, but this is especially important in AF because they are often inventive envelopes developed with a specific purpose (Attia, 2018).

According to the present literature study, there is currently a knowledge gap and a problem in assessing CABS utilizing POE approaches. There is a critical need for POE methodologies to measure occupant engagement, well-being, and productivity. POE approaches that focus on the interaction between technology, the user in the physical environment, and the building administrator must be redesigned. Finally, because CABS are often novel systems and materials, POE will give additional support for their adoption in the building sector.

## 5.3 POE Possibilities for CABS

The preceding section provided a thorough explanation of the difficulties typical POE assessments confront while analyzing CABS:

- There is no real time data gathering
- Unable to assess the interaction between the user and the CABS
- The accurate time of discomfort can not be defined
- POE outcomes are not fed back to inform the operator
- Building experts don't have a benchmark for AF compared with the traditional POE of buildings databases.

Two distinct techniques have been proposed in the literature to address the aforementioned difficulties. The first step is to create a new POE method for CABS; this way, traditional data collection will be avoided, and instead, real-time data will be obtained using dashboard technology. The second option will employ classic POE methods while adapting them to the complexity of the CABS by conducting the POE more than twice under diverse climatic and environmental circumstances. Both techniques have been thoroughly discussed in the sections that follow. It should be noted that the first technique provides more accurate information, but it is more difficult to carry out for low-budget studies; hence, the second strategy is more appropriate for small research projects. However, the lessons from both approaches were collected and combined to develop a novel POE model that meets the complexity of CABS by focusing on user-centric study.

### 5.3.1 Approach I: Dashboard Design and Real-time Data Gathering

Based on their study, Attia et al. created the first method in 2018. The proposed framework allows various users, primarily occupants and operators, to share the management and control of the interior environment and adaptable façades technology. In this sense, the system enables real-time feedback by integrating users and operators in a dynamic and integrated manner. According to the framework, POE should be transformed into a dynamic and participatory process. The built framework focuses on energy savings, maintenance savings, control tactics, productivity, and user experience. The system is primarily based on a central control point connecting users and operators through BMS. Future POE should be built on a platform that gets immediate and constant feedback from the inside environment and the façade system (Jaunzens et al., 2001).

A dashboard has been proposed in this investigation. This dashboard design inspires future POE studies and research to incorporate immediate feedback. Historically, the cause-and-effect chain was far away in time. However, developments in IT and sensor technologies necessitate a radical strategy for POE. The User Interface (UI) gives real-time feedback for comfort and energy performance via this dashboard (Figure 31). Simultaneously, the UI enables interaction between users and the building operator via alert messages or change requests. Users' satisfaction with the functioning of the façade may be immediately conveyed to facility managers. In this way, people have more control over their inside atmosphere and the adaptive technology of their façade (Jaunzens et al., 2001). However, the research stated above is a unique study that focuses on designing and adapting POE for CABS.

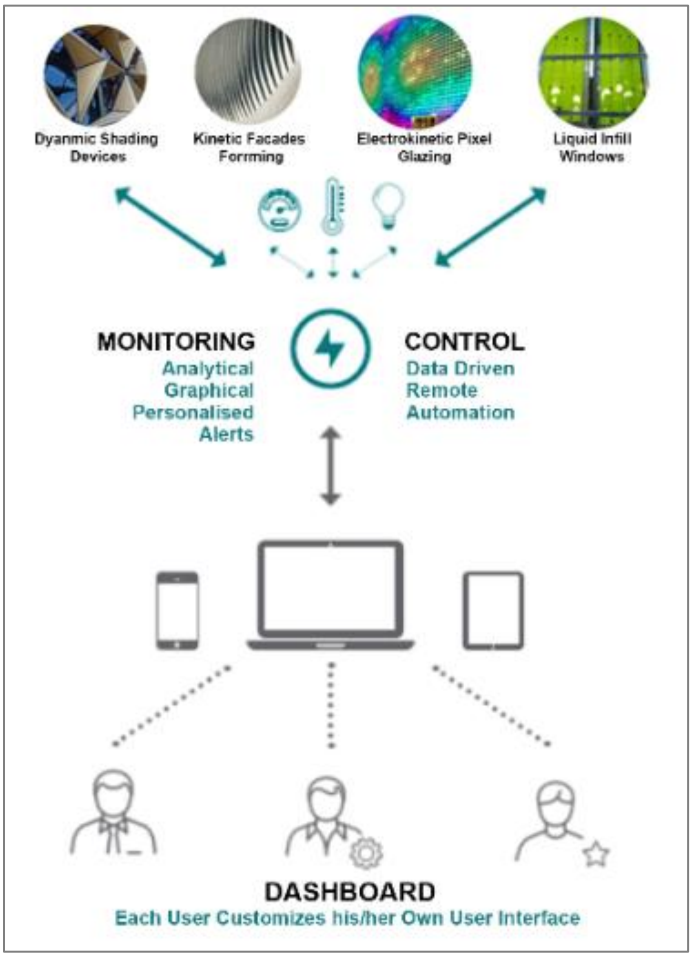



Figure 31: Model of POE for CABS (Attia, et, al., 2018)

Although the suggested model is competitive to CABS complexity, it does not address multi-disciplinary and multi-domain CABS variables. The recommended approach is still not occupant-centric and is mainly designed for the performance of the façade, and it is unclear what comfort factors will be challenged, where data will be stored, or how data will be assessed. As a result, a complete model for POE should be constructed using the idea proposed by this model, which is real-time data collection.

### 5.3.2 Approach II: Conventional POE with Repetition

According to Attia et al., 2018's literature study, the advancement of POE resulted in the creation of two procedural techniques or methodologies: (1) Qualitative methods: (2) Physical Quantitative Methods: a) IEQ evaluation and b) evaluating the energy consumption (Meerbeek et al., 2014) (Bluyssen et al., 2013). However, most of these methods are not developed by third-party, and since they are coming from researchers, they might not be valuable to BMS or designers.

In order to adjust the traditional POE methods in order to meet the complexity of AF, the repetition of the metho is suggested. However, this still highlights the importance of developing an occupant-centric method to examine the occupants behavior in buildings with AF.

The “occupant-centred adaptive façades assessment survey (OCAFAS)” was used to create a survey for this research, which has been verified and developed to find numerous factors that individually relate to persons’ satisfaction, and occupiers’ interaction assessment. The Figure below depicts how the survey for the occupant-centric study for CABS was created. The survey was constructed in stages, including identifying the domains, designing the initial survey, and launching a test to assess the accuracy and reliability of the questions (Attia, 2019)(Figure 32).

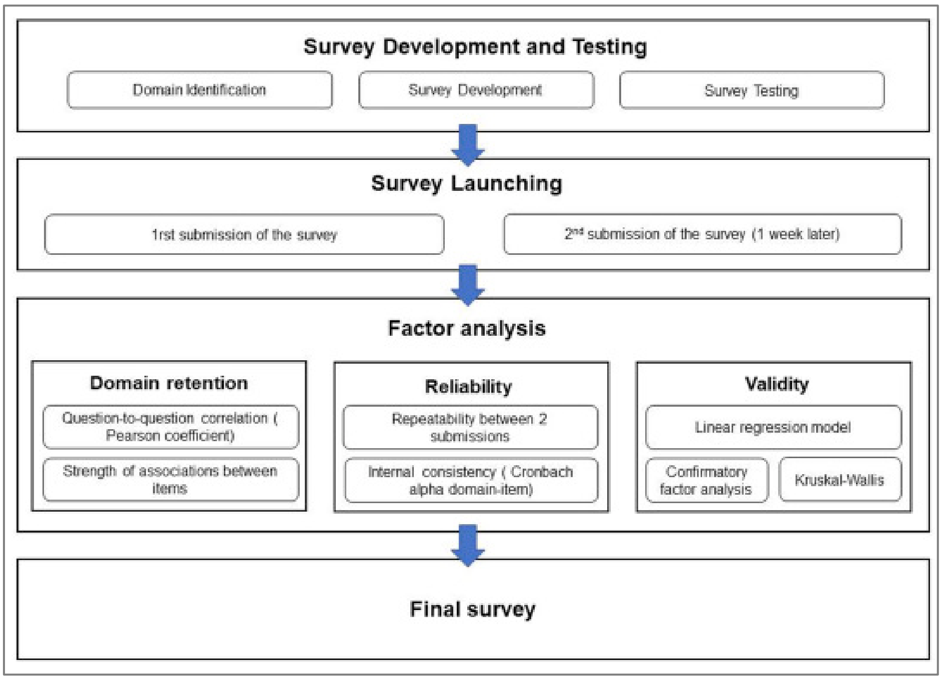



Figure 32: OCAFAS Development (Attia, 2019).

The questionnaire created for the developed model of this thesis, which will be detailed in-depth in the following chapter, was completed using OCAFAS and the same concepts.

## 5.4 Chapter Summary

It was attempted in this chapter to incorporate the keywords discussed in earlier chapters. At the same time, gain knowledge related to the difficulty of CABS assessment, research existing methodologies, and go through the two options for carrying out POE for CABS. The dashboard was created to obtain continuous data in real-time or use the traditional technique but with repetition to obtain more precise data. In the next chapter, a new model for POE compatible with the complexity of CABS will be provided based on the principles learnt from the preceding two methods, user-façade interaction scenarios and building shells behaviour (Figure 33).

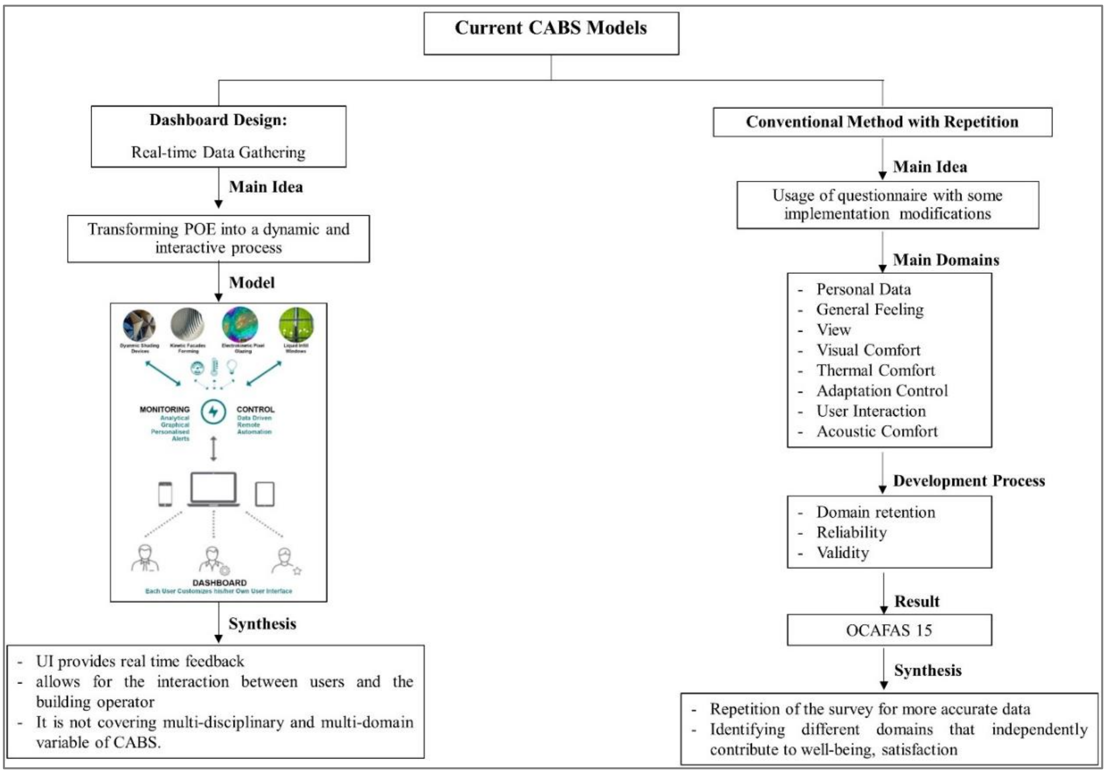



Figure 33: Summary and Synthesis of Current POE Models for CABS (Author, 2021)

# Chapter 6

# DEVELOPMENT OF DYNAMIC CLOUD-BASED POE MODEL FOR CABS

As previously noted, carrying POE for CABS is one of the critical phases that has received limited attention. Previous research would highlight two aspects: a) the requirement for real-time data collecting and b) the legitimate questions that can be addressed. Despite the fact that both studies presented in the preceding chapter are invaluable, they cannot compete with the intricacy and multi-domain qualities of CABS. As the primary goals of this PhD thesis, it has been attempted to design a POE model for CABS that can capture data in real-time, determine the precise time of discomfort while considering user-façade interaction types, and has been designed based on occupant-centric concerns.

The following sections establish the unique paradigm of cloud-based POE and explain the conceptualization and application of the model, plus data collection, storage, and analysis for decision-making based on user satisfaction levels. Following Figure 34 illustrates the three main steps of model development.

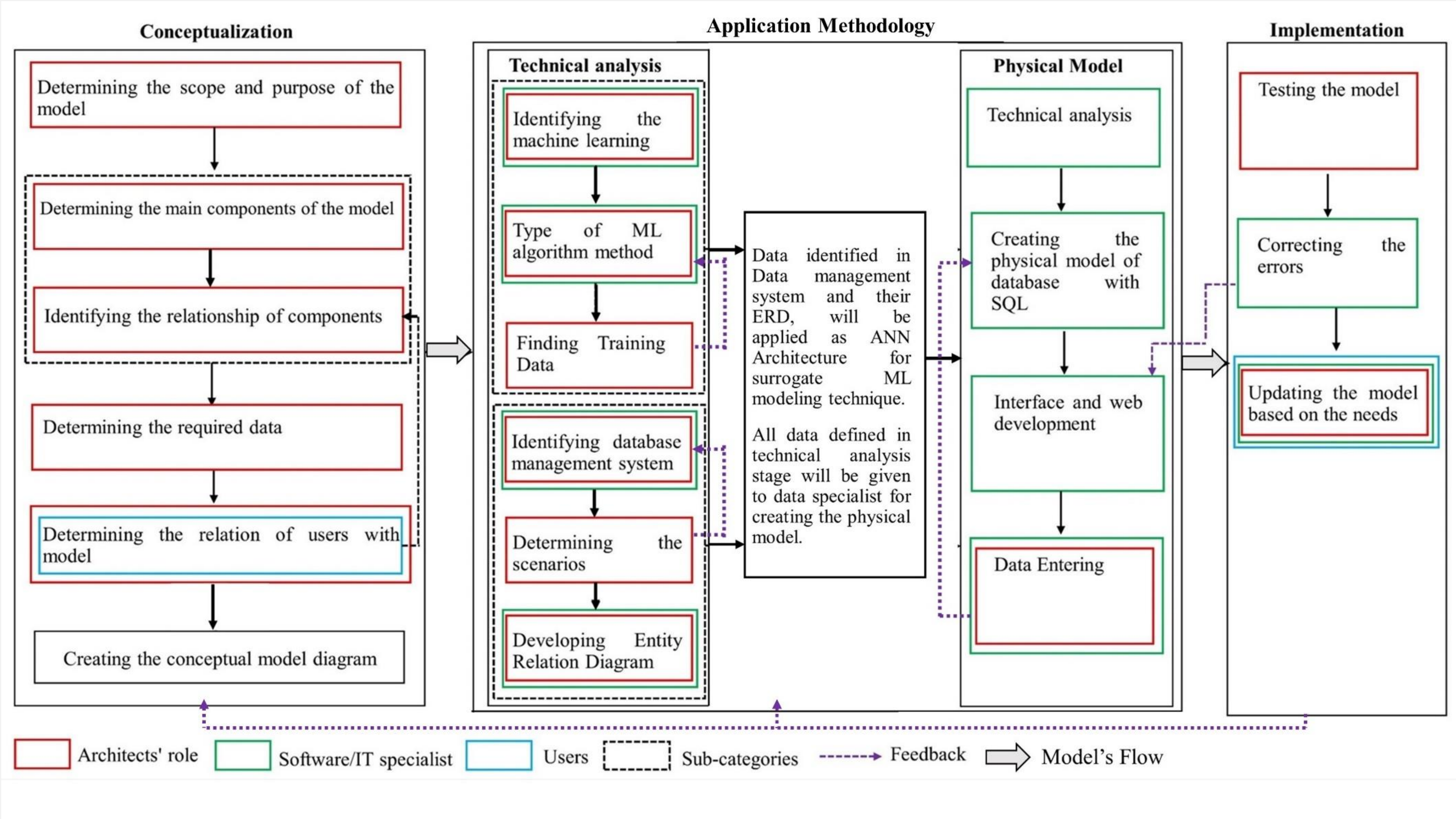



Figure 34: Design Stages of the Model (Author, 2022)

## 6.1 Conceptualization: Cloud-Based Model Design

Because of recent computer advances, data-seeking businesses now have fast access to applications and machine learning (ML) technologies. By leveraging technological advancements, particularly in Internet of Thins (IoT) and Artificial Intelligence (AI) sciences, as well as using sensors and large storage systems to collect data, it is conceivable to construct a model that can compete with the complexity of systems such as CABS.

The following components are required to establish a dynamic POE for CABS based on occupants and assisted by AI technologies. a) Adaptive façade, b) sensors, c) storage, d) IoT device (mobile app). The intended model is presented in Figure 35. The following sections will describe each stage of the model.

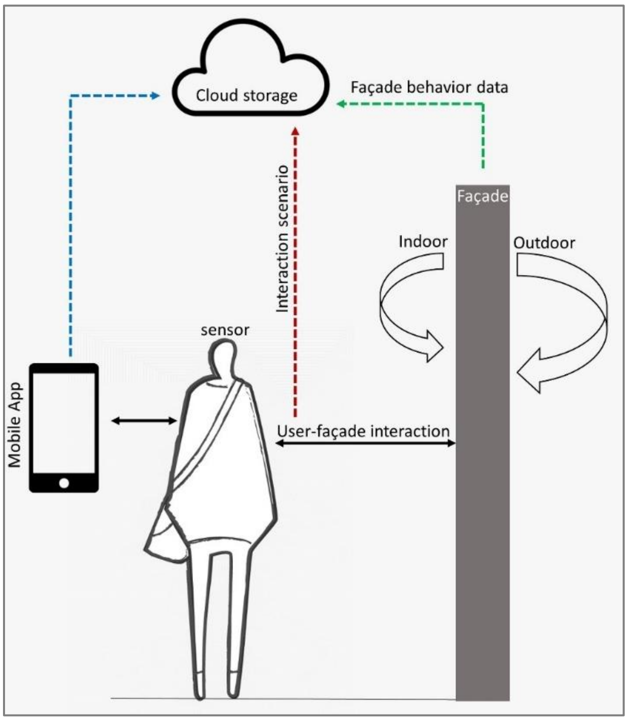



Figure 35: Cloud-based POE for CASB (Author, 2022)

A cloud-based POE is a continuous framework of POE that includes data collection, storage, and evaluation. A cloud is a wireless sensor network that collects physical measurements (quantitative data) such as temperature and humidity. The acquired information for this study is not the building's fixed physical status but the occupants' feelings. As one of the few occupant-centric research in the area, this study attempted to gather exclusively the occupants' feelings toward their physical surroundings and determine the exact time of discomfort and, in general, the level of satisfaction.

In general, three data types will be collected in the cloud: a) physical façade behaviour, b) user-façade interaction type and scenario, and c) data provided by occupants (Figure36). The first two pieces of information may be obtained by researching each instance in the literature (chapter 2), but the most challenging component is getting information from the occupants (Chapter 6).

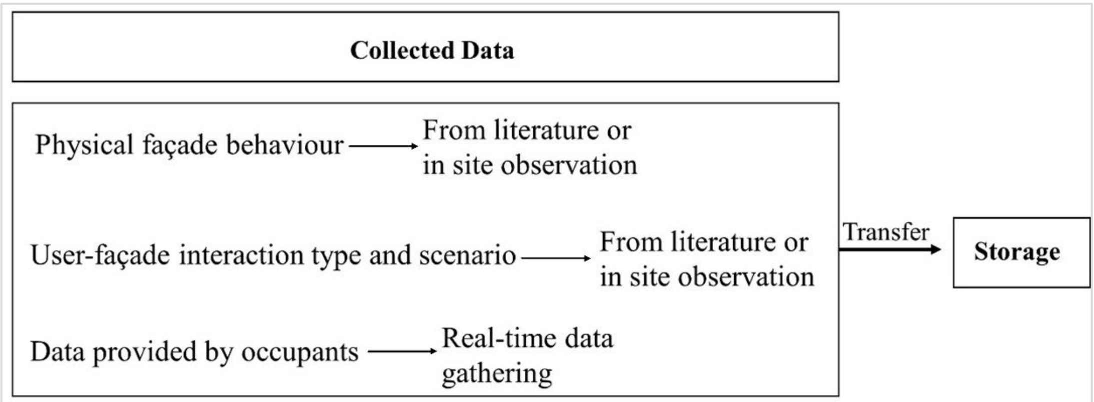


Figure 36: Three Types of Collected Data to Storage (Author, 2022)

The first two sets of data related of physical behaviours of CABS (characteristics) and the type and scenario of user-façade interaction can be collected with a literature review or observation (explained in detail in chapter 2) before applying the model on occupants. The challenging part of this proposal is collecting accurate data from occupants. The goal is to comprehend how occupants react to changing parameters in the building shell in various user-façade interaction scenarios. As a result, sensors must be defined to collect data.

### 6.1.1 Dynamic Cloud-Based Model's Sensors

A sensor is a device, component, gadget, or subsystem that detects events or changes in its surroundings and transmits the data to other electronics. The sensitivity of a sensor describes how much the sensor's output varies as the input amount being evaluated differs. As per biomimetic concepts and investigations, the notion of sensors is derived from the natural world. Today's sensors are not even close to the delicate and sophisticated biological sensors found in the human body, such as the fingertips.

One ongoing study on human behaviour in the occupant-centric field of CABS research involves employing sensors to observe human behaviour and acquire essential data. However, based on what was mentioned, the notion of utilising the residents as sensors for this study arose.

The buildings' occupants are sensitive to environmental and physical changes. The human body senses and detects sensations that might translate to pleasure or discomfort, satisfaction or dissatisfaction, and stores them in the brain at the precise time of occurrence. As a result, since the research developed over occupant-centric research principles, occupants are the most acceptable sensors for acquiring data.

As with all sensors, the sensor must be linked to a secondary device to relay data. The concept is the same in the scenario described for this model. The sensors (human brain) detect the discomfort, but the data must be sent and stored to be evaluated. A smartphone app can gather data on occupant perceptions (qualitative data) and update the data repository in real time.

Following Figure 37 presents the working mechanism of the model's sensor in three phases; 1) the environmental changes in the surrounding has been felt by the occupants, 2) the qualitative data translated into the human brain as discomfort, 3) the detected data should be transfer from sensor to storage which requires a secondary electronic device (Mobile app). Later, the collected data should be translated into quantitative data to be evaluated and synthesized.

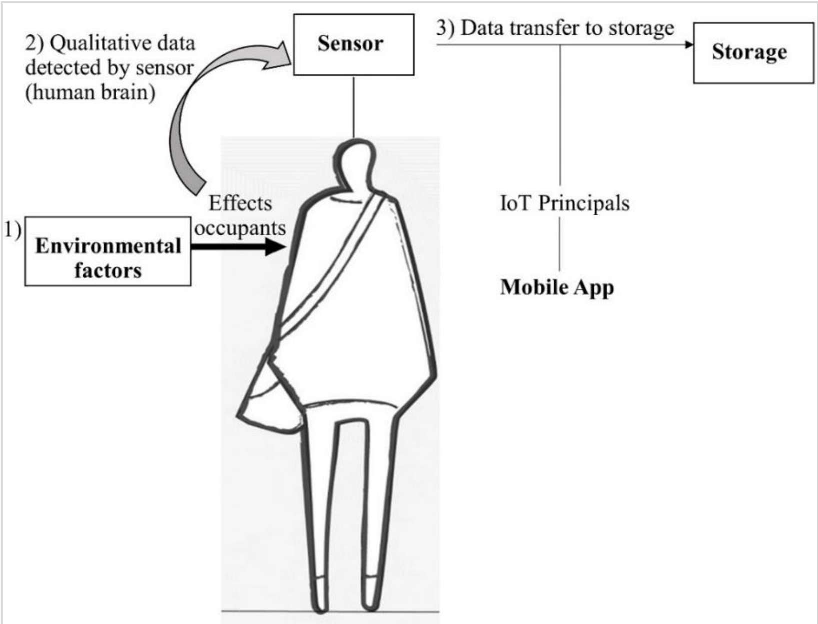



Figure 37: Occupants Working as Sensors for Model (Author, 2022)

### 6.1.2 Smartphone Application- Data Collection

POE and human-computer interface (HCI) design concepts were considered when creating the smartphone app. The comfort metrics established in Chapter 4 will be questioned to design an app recording subjective occupant rating data. The mobile app's primary goal is to have a high response rate; hence, a simple, quick-to-complete survey was created. The survey is based on prior research called OCAFAS (Appendix 2), explained in length in Chapter 5.

To gather the data, the mobile app must answer a set of questions according to the changes on the façade and its influence on users. To be easier to show the question in the written thesis format, they have been illustrated in the form of the survey (Appendix B), although in reality, they will work with the mobile app and within different steps.

The survey created for this study aims to collect two types of data. To determine which domains impact occupant satisfaction most and which have the least, in phase one, occupants assist the analysis by assigning weight to each domain, allowing the Multi-criteria analysis to be carried out using a simple additive weight procedure. The second set of questions produced based on the OCAFAS valid survey provides data for determining the degree of satisfaction of users in office buildings with various user-façade interaction systems with the help of SSPS software evaluation (Attia et al., 2019). The subsections of this chapter discuss the evolution of each question set in depth.

**6.1.2.1 Domains Identification**

to develop and carry out any survey, the main domains of the survey should be identified in the first stage. The domain categorization for this investigation was generated based on a literature review. In total, eight domains were created to be questioned in the questionnaire. 1) personal information 2) overall impression 3) perspective 4) visual comfort 5) Thermal comfort 6) Adaptation management 7) Interaction with the user 8) Acoustic comfort.

It should be noted that these areas were questioned based on the individuals' feelings, and comfort standards did not apply. This study was designed with the user in mind.

It attempted to examine users' general satisfaction and productivity of adaptable façade buildings using various user-façade interaction approaches (Attia et al., 2018).

After identifying the study's primary domains, the survey is developed in two stages. The procedures for creating the final survey are covered in the next section.

#### 6.1.2.2 Survey Development

Section A: The first set of data collection will be carried out once at the beginning of the research project since the given data (value to satisfaction factors) is the fixed data of the study. Fixed information must be obtained during the initial data collecting step. This section ranks the comfort factors in priority order, from most essential to least important. By ranking the comfort factors, it will be possible to translate occupants' feelings (intangible data) to numeric data (tangible data). These questions will be addressed once at the start or conclusion of the study process. The information gathered from these questions will assist the researcher in weighing each comfort factor concerning the occupants (occupant-centric concept), which will subsequently be valuable for decision-making analysis.

Section B: the survey domains were identified, resulting in a survey with six domains experimentally considered connected to occupant well-being in office buildings with adaptable facades (Attia et al., 2019). The survey was developed within two general sets of questions related to personal information and satisfaction. As shown in Appendix B, the survey categories and items were deemed appropriate for inclusion in an initial 14-item OCAFAS survey.

Occupants must respond to a survey at a specific time when there is a modification and behavioural change on the building shell (Figure 28). As previously stated, the mobile app will notify residents to complete the survey (Figure 39). With this repeat at a specific (recorded) time, it will be feasible to assess the occupants' satisfaction level and pinpoint the exact period of discomfort. It will be possible to understand occupants' perceptions of any changes in CABS by correlating the period of discomfort with the occurrence of modifications on the façade during that time.

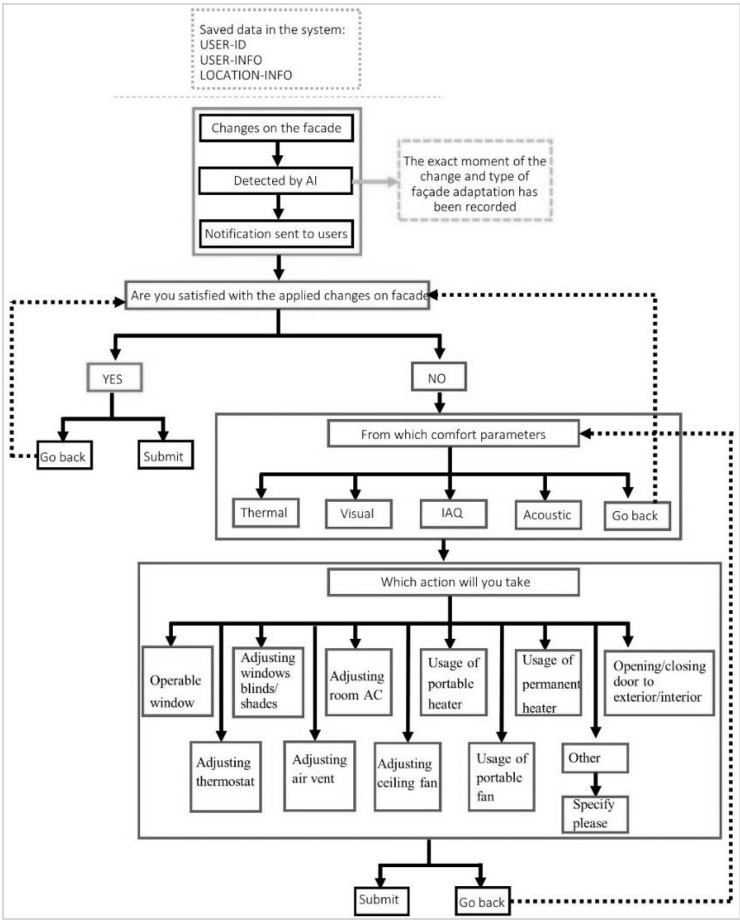


Figure 38: Working Mechanism of a Mobile App (Author, 2022)

To collect the seeking data, IoT principles have been utilized. As a result, the sensors (occupants) will be linked to the cloud via the mobile app. It is critical to determine the time of data gathering at this stage. The following sections explain how the model's

AI works, how notifications operate, and how data is collected and transferred to the cloud.

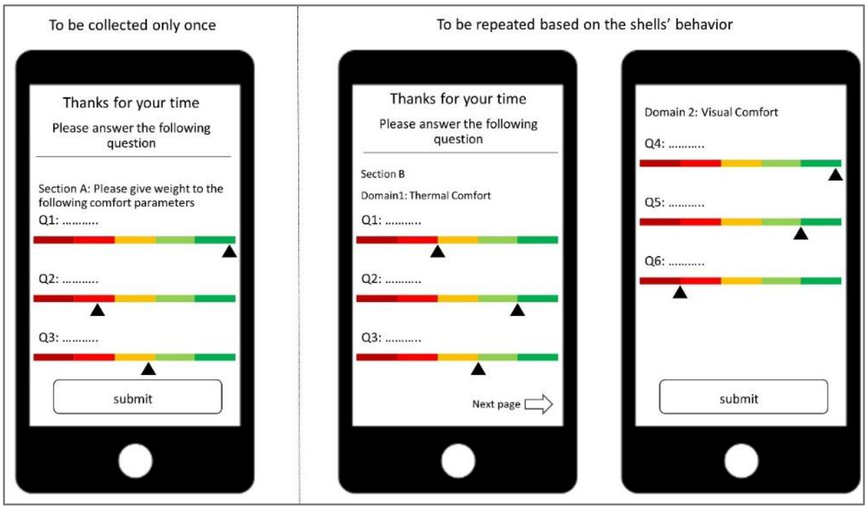


Figure 39: Mobile App for Data Gathering (Author, 2022)

### 6.1.3 Dynamic Cloud-Based Model's AI Framework

AI advancement is opening up new chances to enhance people's lives worldwide, from industry to healthcare to academia. It also raises additional concerns regarding effectively including equality, interpretability, confidentiality, and safety in these platforms.

AI-powered products must train their fundamental machine learning (ML) model to discover patterns and connections in data to make recommendations. This data is referred to as training data and might include collections of photos, videos, text, audio, and other media. Researchers can leverage existing data or gather information specifically for training the system. The model's output is directly determined by the training data obtained and how those data are labelled (Alexsoft, 2018).

When developing any product in a human-centred manner, the most crucial considerations are: who are the users? Which of their problems should be addressed? How will the issue be resolved? As a result, it is critical to identify which user challenges are suitable for AI and how to quantify success. Important considerations:

- Discover the point where user requirements and AI abilities intersect.
- Consider automation
- Create and test the reward function.

As previously said, the primary component and practical challenge to be tackled for this study are the lack of occupant-centric studies on occupant satisfaction levels in buildings using CABS. CABS' complexity, multi-ability, and multi-domain qualities make carrying a POE difficult for this system. Once the part of the study that needs to be improved has been determined, researchers must assess which viable solutions require AI and which are significantly enhanced by AI (n.d., 2019).

To create the suggested POE model, the initial step must be to collect accurate sources of façade behaviour for training data. In this stage, the behaviour of the façade should be thoroughly observed throughout various periods, and data should be collected. These training data (façade behavioural changes) will assist the model's AI learn the system's behavioural pattern.

When the model is trained using the data obtained, the database creates an AI-powered app that identifies façade modifications. As a result, when the AI of the model detects changes on the building façade based on the training data provided, the sensors (occupants) will be notified to begin filling out the survey. Using this technology, it will be feasible to collect real-time data from occupants and determine the exact moment and type of discomfort based on façade behaviour. This AI-powered dynamic POE model will be CABS-compatible in terms of complexity. The following section explains the model's notification-based mobile app interacting with AI.

### 6.1.4 Notification-Based Data Collection Operation

One of the most challenging aspects of analyzing CABS is determining the exact timing of discomfort related to shell behaviour due to their flexibility. To gather data at the right time and determine the relationship between CABS modifications and occupant satisfaction and comfort, the researchers should specify when the data should be collected.

In this case, the app must have physical behaviour data of the shells. As a result, the app informs the sensor (users) to gather information about their perception of changes. The comparison and linking of real-time data from users and building behaviour at that precise time can emphasize the occupants' contentment or dissatisfaction with the shell behaviour based on set comfort factors.

To run the model's notification phase, a study of the shell's behaviour must be conducted in advance, or sensors must be linked to the shell so that whenever the façade is modified, the data is sent to the model's AI, and a notification informs users to answer the prepared questions. Aside from the behavioural modifications of the building shell, the types and scenarios of user-façade interaction must have been studied by researchers and included in the model's AI. In this situation, the research results may be linked to the interaction types to determine the best solution from the standpoint of the occupants (Figure 40).

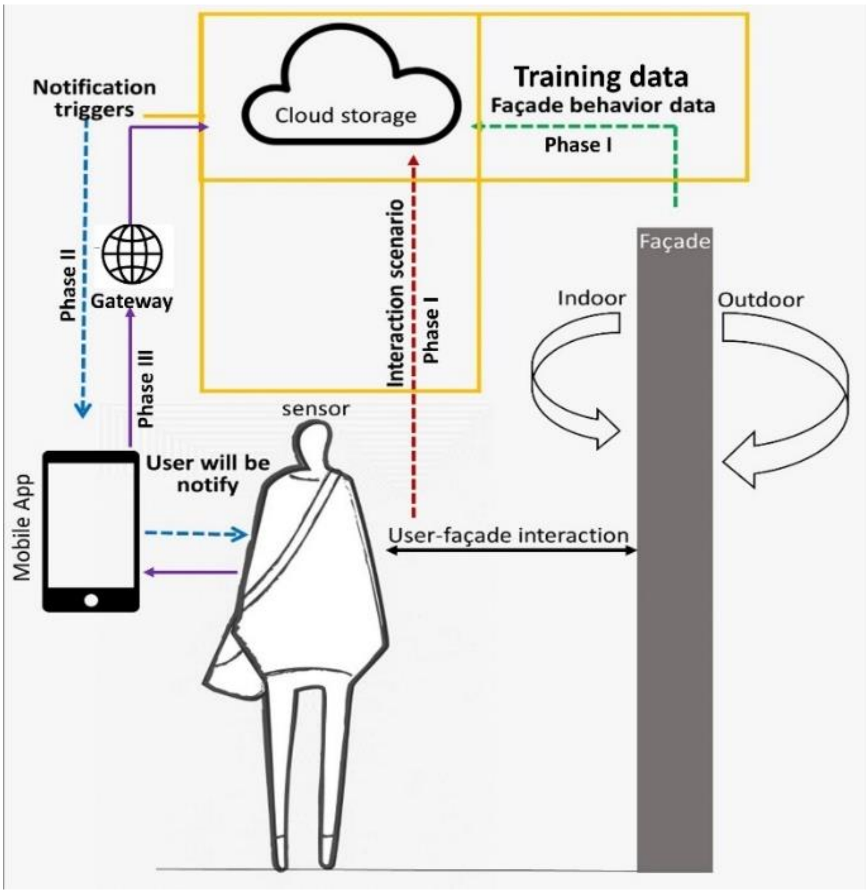


Figure 40: Notification Triggers for the Mobile App (Author, 2022)

### 6.1.5 Data Storage- Cloud-Based Storage

In such models, the amount of data acquired is enormous and continues to grow; hence, all collected data will be stored in the cloud with the assistance of a web server. Later, the data obtained within the stipulated time frame must be examined to improve decision-making for the occupant-centric study.

In general, cloud storage is a service that allows data to be stored on remote servers. Cloud storage works by helping researchers obtain data over the internet, permitting them to store and retrieve information anywhere in the globe where internet access is available. Thus, with this technology, researchers may work on any project from anywhere globally and have access to the data.

Furthermore, the data acquired in the cloud may be shared with other research organizations' servers. As a result, the POE feedback may support other initiatives, and the research area will continue to progress.

Using a cloud-based storage system for recent scientific research, such as this thesis, has the following advantages:

- Usability and accessibility: Almost all cloud services include an easy-to-use user interface capability.
- Security: The data is saved throughout multiple servers in the cloud, so even if one of the data centres fails, the information will be maintained by the other data centres, keeping the data secure and overseen.
- Cost-efficient: The research teams can save money on internal resources by embracing online information storage. The organization does not require internal resources or assistance to maintain and keep their data; the cloud storage vendor handles everything with this technology.
- Automation: Cloud storage functions similarly to a hard disk, and storing any file in the cloud will not interfere with any ongoing tasks.
- Synchronisation: The sync functionality is provided by every storage vendor.
- Scalable: Cloud storage is scalable and flexible.
- Disaster recovery: If the system fails or loses data, it can recover data using the backup plan (Vinay, 2020).

### 6.1.6 Accuracy of Data

One of the problems the model may encounter is the trustworthiness and correctness of the data provided by occupants. The proposed model will aid researchers in repeating the POE within a set time frame, which may be frustrating for the occupants and cause the data to be inaccurate. To address this issue, the use of environmental sensors (such as thermal, humidity, acoustic etc.) is suggested. This model, as occupant-centric research, is meant to gather occupants' feelings purely and not consider the comfort standards. However, environmental sensors are proposed to study the ecological conditions and assess the comfort parameters based on the standards to cross-check the collected data.

Adding environmental sensors gather data from the research space's interior and outdoor areas, and the obtained data will be uploaded to the cloud via the IoT technique. Later, the precise moment the occupants communicated with the cloud may be provided, and the occupants' data will be cross-checked with sensor data. In this instance, the accuracy of the occupants' data may be validated to a certain extent.

The sensors do not monitor the inhabitants' activity to ensure occupant privacy but instead focus on the current environmental condition. In addition, the app must be created following the General Data Protection Regulation (GDPR) in terms of occupant privacy. The GDPR controls individuals' data processing by an individual or a company (Camilleri, 2020). As a result, the app will not retain any personal data about the occupants and will always get their data when they use it.

Thus far, the study spoke about the significant parameters of the AI-Powered dynamic cloud-based POE. Although two significant portions have still to be addressed; 1) application of the model, 2) implementation of the model, and later the questionnaire and the data analysis methods need to be studied as well. Figure 41 depicts the dynamic cloud-based POE model conceptualization created in this thesis work, from first to end.

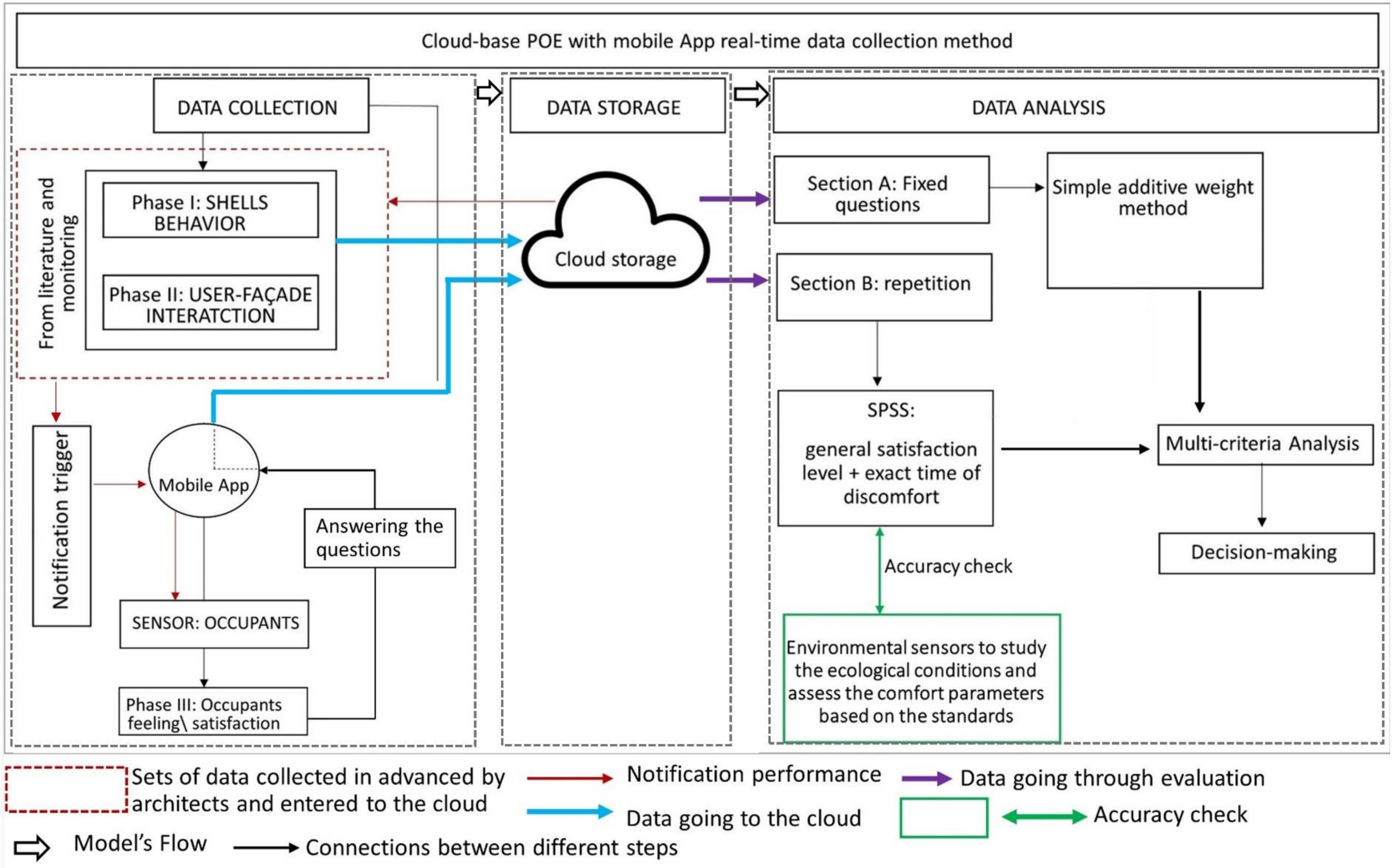



Figure 41: Cloud-based POE Model with Mobile App Real-time Data Collection Method (Author, 2022)

## 6.2 Application Methodology of the Model

After conceptualizing the cloud-based model, this section of the study focuses on the application of the model. The model's application will be explained in different sections; a) Machine Learning and Training Data, b) Database Management System type, and c) Entity Relationship Diagram.

### 6.2.1 Machine Learning and Training Data

AI and its thread, machine learning (ML) technologies, have advanced fast in recent years. Its application appears to be expanding in various industries ranging from automotive to health, law to marketing. Likewise, similar technologies have begun to be applied in the construction and architectural industries. These innovations are employed in many areas of architecture, including feasibility studies, project management, energy efficiency, and intelligent building design.

ML is regarded as a subfield of AI study. ML algorithms build a statistical-based logical framework based on predictions even when they are not given explicit orders to perform the task at hand. This analytical system is built using a mathematical model based on groups of data specified by the user and referred to as training data.

ML algorithms estimate new output values by using past data as input (Figure 42). In general, the most used ML algorithm today is the ML supervised algorithm. The supervised algorithm learns from being given the right answer and eventually predicts the right response (Moghtadernejad et al., 2021).

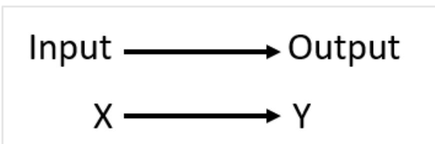



Figure 42: Supervised Machine Learning Algorithm (Author, 2022)

One of the ML models with the supervised algorithm that can be used in engineering and architecture is surrogate modelling. Surrogate modelling can be used for sensitivity analysis to investigate product behaviour when design factors vary. In this manner, this modelling method's utilization can fall into the proposed model's scope.

A data-driven technique is used to train a surrogate model. It collects training data by probing simulation or qualitative analysis outputs at numerous intelligently chosen points in the design parameter space. The statistical model may be developed based on the provided dataset by collecting the pairs of inputs (design parameters) and their associated outputs into a training dataset. Surrogate modelling will be applied within three main phases:

Phase 1: Sampling- The modelling process begins with the generation of initial training data. To do this, carefully selected samples of the design parameters from their parameter space will be used.

Phase 2: Output Evaluation- Once the first training samples have been found, they must be studied to find their matching output values. Then the initial training dataset will be given after combining the pairs of selected training samples and their matching output value.

Phase 3: Building the Surrogate model- In this stage, the surrogate model can be built utilizing the training data acquired in the previous step. To assist the model training process, recognized machine learning procedures of model validation and selection should be used (Ekici et al., 2021)

Since innovations in the field of façade design are ongoing, the model needs to be updated. The surrogate model is an active model that is particularly valuable for the suggested cloud-based model of this thesis (Figure 43). An analyst generally cannot predict how many samples will be needed to create an appropriate surrogate model. The complexity of the estimated input-output relation determines this. As a result, as the training advances, it becomes more sensitive to enrich the training dataset which is referred to as active learning.

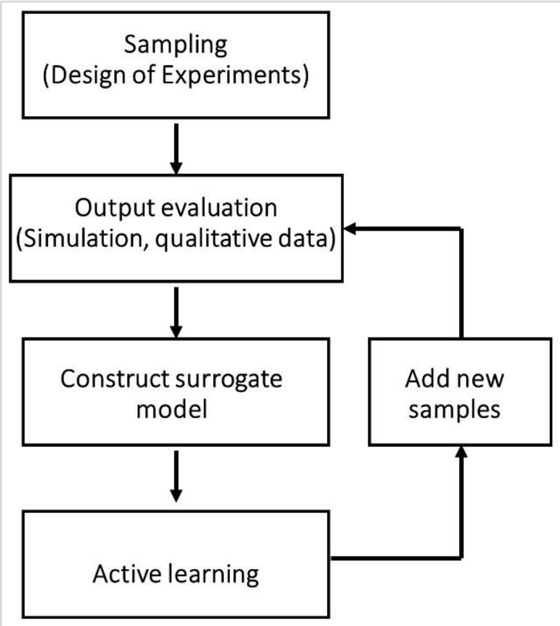



Figure 43: General Framework of Surrogate Model (Guo et al., 2021)

According to the surrogate modelling, the sampling of the different CABS with different prototypes must be done in the first phase. In the second phase, the Artificial Neural Network (ANN) architecture method will be used to predict the building performance. ANNs have commonly used approaches in ML fields to forecast different elements of building performance and relate to the second stage of the ML phase. This is due to the fact that ANNs can handle enormous sample volumes for numerous factors and predict performance with high accuracy. Then accordingly, the surrogate model for ML can be constructed. Figure 44 illustrates the framework of machine learning for a surrogate model of the study.

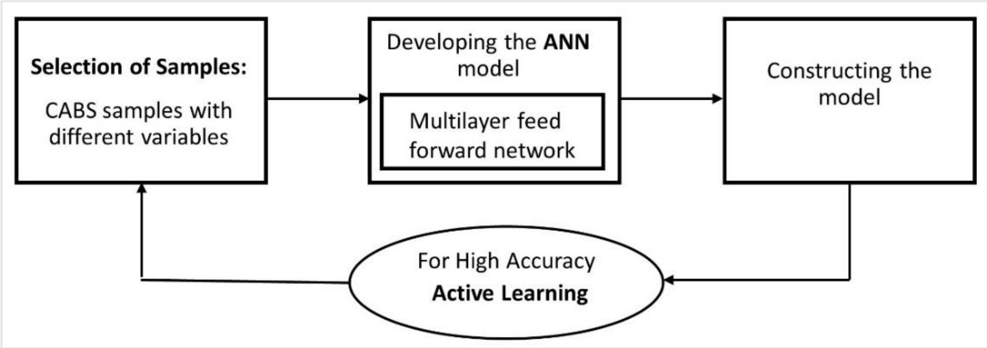



Figure 44: The Framework of Machine Learning for Surrogate Model (Author, 2022)

An Artificial Neural Network (ANN) is a brain-inspired information processing paradigm. ANNs, like humans, learn via experience. An ANN is trained for a specific application, such as pattern recognition or data categorization, through a learning process. For this study, the interconnection ANN method has been used.

Interconnection refers to how processing components of ANN are linked to one another. As a result, the placement of these processing components and the geometry of interconnections are critical in ANN. These configurations always include two layers shared by all network architectures: the input layer and the output layer. The input layer buffers the input signal, and the output layer provides the network's output. The third or fourth layers are the Hidden layers, in which neurons are not preserved in either the input or output layers (Gupta and Raza 2019) (Figure 45).

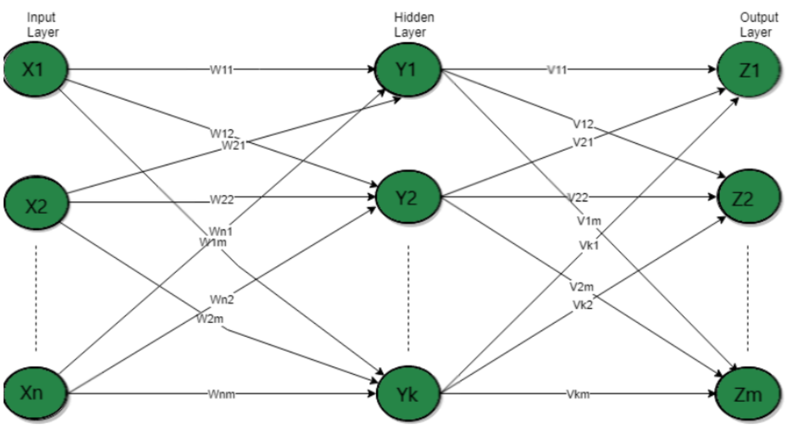



Figure 45: Multilayer Feed Forward Network Framework (Gupta and Raza, 2019)

In this study, the interconnection ANN method has been used for the model to be trained and predict the façade behaviour which consequently help the model's notification mechanism. For the ANN input layer, different CABS prototypes have been studied. Hidden layer one will be the environmental factors (exterior) which can cause the changes in the input parameters and directly affect façade behaviour. Hidden layer two will be the objectives of the façade focusing on the general comfort parameters that directly impact users feeling. And lastly, the output layer will be the application of the changes on the façade. The following Figure 46 illustrates the defined layers of the ANN architecture of the model. Presented prototypes in the figure are limited and only show the working mechanism of ANN for the surrogate model and will be completed based on different research projects.

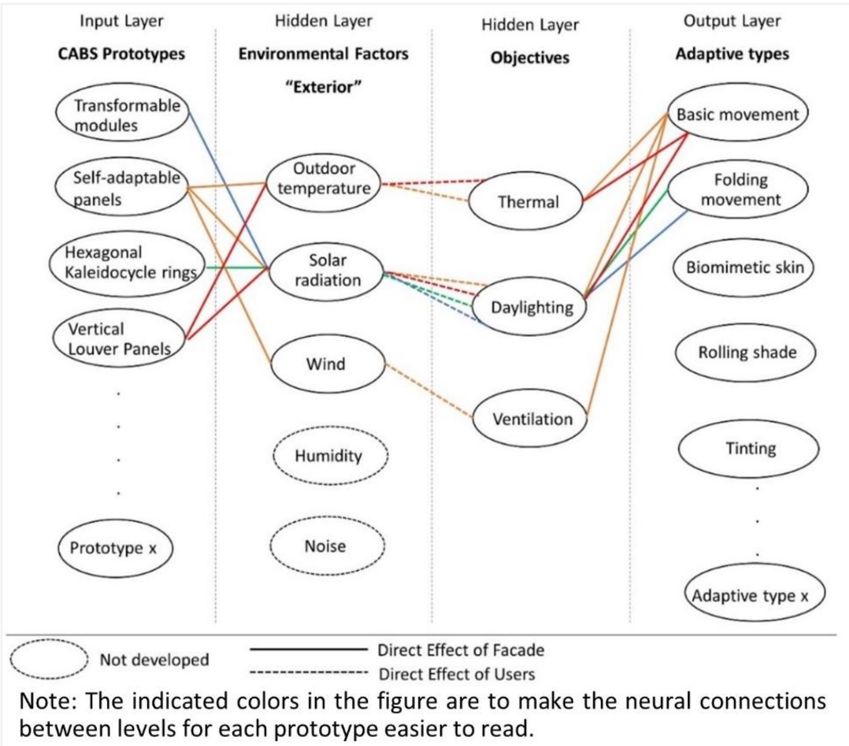



Figure 46: ANN Architecture of Surrogate Model (Author, 2022)

Defining the ANN provides the training data for the machine learning model. Accordingly, with the help of IT experts, the model can be trained. Since the active surrogate modelling has been applied, the ANN can be updated throughout further research to increase the accuracy of the model prediction over time.

### 6.2.2 Database Management System

A database is a structured collection of information often kept electronically in a computer system. A database management system (DBMS) is generally in charge of a database. The data, the DBMS, and the applications linked with them are referred to as a database system, frequently abbreviated to the just database.

To facilitate analysis and information querying, data in the most prevalent types of databases in use today are often structured in rows and columns in a sequence of tables. After then, the data may be readily accessed, amended, updated, and organized. Most databases employ structured query language (SQL) for creating and querying data.

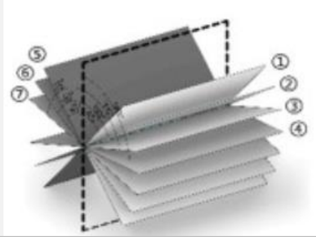
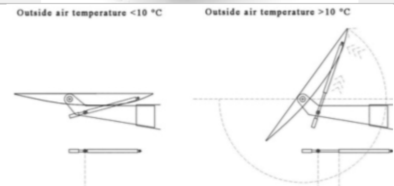
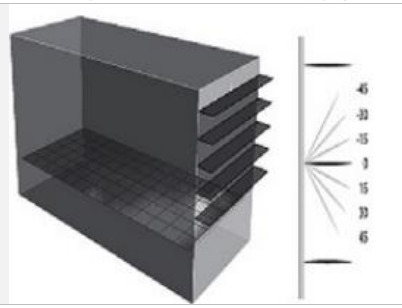
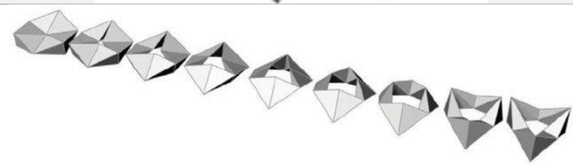
There are different types of databases (relational database, object-oriented database, NoSQL database and so on). Each selection depends on how the researcher or organization wants to use the data. For the model of this study, the relational database management (RDBMS) system has been selected.

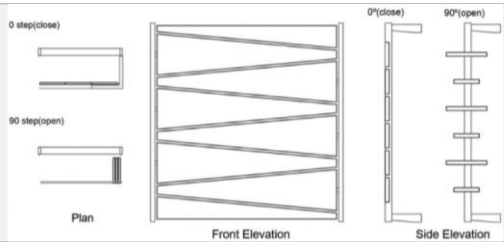
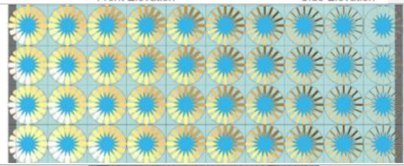
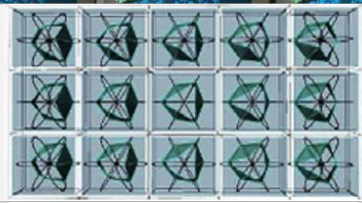
A relational database management system (RDBMS) is a form of database that stores data in tables and may be used in conjunction with other stored datasets. Most of today’s IT systems and applications are built on relational databases. Relational databases are built to manage large amounts of data and complicated queries. Multiple tables are common in contemporary databases. Data is frequently maintained in many tables, sometimes called ‘relations.’ These tables are organized into rows, which are also known as records, and columns (fields) (Cooper, 2019).

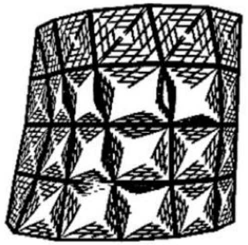
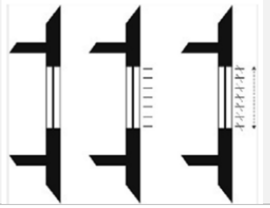
To develop an RDBMS, the required data must be organized within tables in the first step. Later, tables can be updated, and new relations between tables can be defined. For this study, the leading data was gathered within five main groups: a) adaptive façade prototypes, b) users' information, c) influential factors (Human factors and environmental factors), d) users' control factors and e) façade movement types.

Adaptive façade prototypes have been classified as follows. The following Table 17 describes the façade movement types of each prototype since they are directly related.

Table 17: Adaptive façade prototypes and movements typologies (Tabadkani et al. 2021, amended by author, 2022)

| # | façade prototypes | Movement's typologies | Adaptive type | Pictures and/or Drawings of Prototypes |
|---|---|---|---|---|
| **1** | Transformable modules (Shi, et al., 2020) | Rotational | Folding* |  |
| **2** | Self-adaptable panels (Ricci, et al., 2021) | Rotational | Basic movement ** |  |
| **3** | Vertical/Horizontal Louver Panels (Grobman, et al., 2017) | Rotational | Basic movement |  |
| **4** | Hexagonal Kaleidocycle rings (Wagdy, et al., 2015) | Rotational and Translation | Folding |  |

| | | | | |
|---|---|---|---|---|
| **5** | Vertical panels, Wedge-shaped flat panels (Lee, 2019) | Rotational | Folding |   |
| **6** | Louvers and Rosette skin (Tabadkani, et al., 2018) | Translation | Basic movement |  |
| **7** | Individual movable modules (Jayathissa. Et al., 2018) | Rotational | Basic movement |  |
| **8** | Mood Swing (Moulton, et al., 2018) | Rotational | Folding |  |
| **9** | Kinetic hexagonal patterns (Pesenti, et al., 2015) | Rotational and Translation | Basic movement |  |
| **10** | Multi-layered adaptive skin (Hosseini, et al., 2019) | Rotational | Basic movement |  |

| | | | | |
|---|---|---|---|---|
| **11** | Shape Variable Mashrabiya (Al Bahr Towers, 2022) | Rotational and Translation | Basic movement |  |
| **12** | Kinetic cladding [60] | Rotational | Basic movement |  |
| **13** | Blind and Blanke | Rotational | Biomimetic |  |

*Folding: foldable structures to implement three-dimensional changes over the façade.
** Basic movement: façade includes numerous shading units that can be adapted through a single or multiple basic motion typologies.
***Biomimetic: material-based actuators are developed to trigger the adjustment of future Afs.

In the second phase, the model's influential factors were identified according to the study of Koyaz and Ünlü in 2022. For this model, two main categories have been defined: a) influential human factors and b) influential environmental factors (Table 18). Lastly, the users' control types of adjusting the indoor environment to meet their comfort level must be defined (Table 19).

Table 18: Influential factors (Koyaz and Ünlü, 2022)

| **Influential factors** | |
|---|---|
| **Human factors** | **Environmental** factors |
| Age | Outdoor temperature |
| Gender | Solar radiation |
| Nationality | Wind |
| Location in the office | Humidity |
| - | Noise |

Table 19: Users' control types (Author, 2022)

| # | **Users Control Types** |
|---|---|
| **1** | Adjusting windows blinds/ shades |
| **2** | Adjusting room AC |
| **3** | Usage of portable heater |
| **4** | Usage of permanent heater |
| **5** | Opening/closing door to exterior/interior |
| **6** | Adjusting air vent |
| **7** | Adjusting ceiling fan |
| **8** | Usage of portable fan |
| **9** | Adjusting thermostat |
| **10** | Operable window |
| **11** | Others |

After identifying the primary data within different tables, it is possible to develop various scenarios to display the relationship of the data. Scenarios have been presented in Table 20. And three scenarios have been explained in written format to make the table more understandable. Table 20 presents some possible scenarios since the number of scenarios can be numerous. This table can be updated according to the different research buildings with various prototypes, control factors, etc. However, following explains one of many possible scenarios from beginning till data evaluation in a hypothetical context for better understanding of the model (Figure 47).

Scenario 1: the CABS's prototype selected for this scenario in Transformable modules. This prototype is adaptive this component according to the load of solar radiation and consequently will affect the visual comfort objective. In a sunny day, when the solar radiation on the building shell is extreme the transformable models begin to move. The changes appeared on shell due to the solar radiation in certain hours will change the visual accessibility of the occupants towards outside while working inside the office building. At this moment, hypothesis will come up for researchers and architects.

- Are these changes affecting the satisfaction and productivity level of occupants?
- Are these changes at the moment cause distraction?
- Are occupants still comfortable with the level of visibility to outside?

Thus, at this stage to find answer for above hypothesis, the usage of dynamic model to provide real-time data is important. In the proposed model, as researchers already studied the façade behaviors, the changes on shell will be predicted by AI model (training data) and notifies the occupants to answer few quick questions only related to visual comfort as that is the objective in this case.

At this moment, occupants are going to answer the questions. The positive answer to the questions in regards on changes on shell will end the survey and data will be transfer. The negative answers towards the changes, will direct occupants to next questions related to what kind of actions they will or want to take in order to provide themselves the required comfort. For example in this scenario if occupants need to change the adjusting shading devices direction, or if they are willing to change their sitting area in the office if possible.

After the answering step, the transferred results will be evaluated. In the first step the results will go through SPSS program for finding the general satisfaction level. If the result is a high number, it shows occupants accepting the changes and system is working properly according to occupants. If the number is low, it indicates occupants are not happy with changes and some modifications must be applied on the shell. The decision for modifying the shell can be taken according to what actions occupants did to make the environment comfortable.

All the scenarios and results will be stored in the cloud. With each research done on this field the database will be updated. After having various scenarios and results in the system, a multi-criteria analysis can be applied on the data. In this manner, researchers can compare different scenarios and satisfaction level and find the best possible scenario by considering occupants feeling. This part of evaluation will be helpful for future decision making for building shell design.

The results coming from the proposed model can help both researchers and architects for having more updated data in hand to design systems more responsive towards occupants needs in the future.

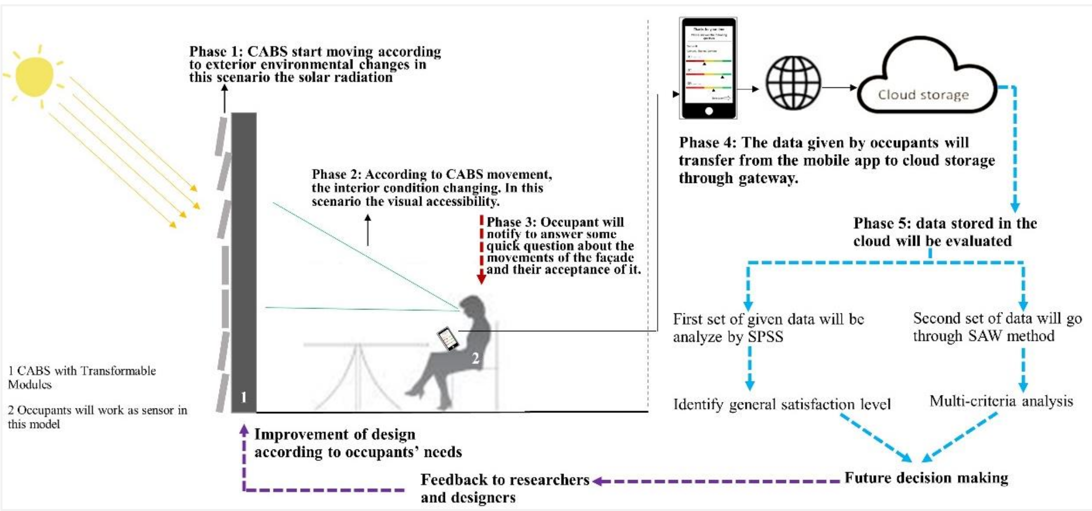


Figure 47: Illustration of Hypothetical Scenario from the Model (Authors, 2022)

Table 20:Relation of the different data in the database (Author, 2022)

| S# | Prototype | Influential Factors | | | | | With an objective to affect comfort and energy usage | | | | | Control type might be applied (According to Table 19) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Environment Factor | | | | | | | | | | |
| | | Temperature | Solar | Humidity | Wind | Noise | Thermal | Visual | acoustic | IAQ | Energy | |
| 1 | Transformable modules | | | | | | | | | | | 1 and 9-10 |
| 2 | Self-adaptable panels | | | | | | | | | | | 2-10 |
| 3 | Vertical/Horizontal Louver Panels | | | | | | | | | | | 2-10 |
| 4 | Hexagonal Kaleidocycle rings | | | | | | | | | | | 1 |
| 5 | Vertical panels, Wedge-shaped flat panels | | | | | | | | | | | 2-10 |
| 6 | Louvers and Rosette skin | | | | | | | | | | | 1 |
| 7 | Individual movable modules | | | | | | | | | | | 10 |
| 8 | Mood Swing | | | | | | | | | | | 1and 9-10 |
| 9 | Kinetic hexagonal patterns | | | | | | | | | | | 1 |
| 10 | Multi-layered adaptive skin | | | | | | | | | | | 2-10 |
| 11 | Shape Variable Mashrabiya | | | | | | | | | | | 1 |
| 12 | Kinetic cladding | | | | | | | | | | | 1 |
| 13 | Blind and Blanke | | | | | | | | | | | 1 |
| Colour codes | | Not developed | | | | | | Applied | | | | |

*All influential human factors can affect the users' behaviour in accordance with façade changing, which will create different scenarios.

After defining the primary data for the database and the general relationship between them, the Entity Relation Diagram (ERD) can be drawn.

### 6.2.3 Entity Relation Diagram

Entity Relationship Diagrams (ERDs) are a sort of structural diagram used in database architecture. An ERD comprises several symbols and connections that depict two crucial pieces of information: the primary entities inside the scope definition and their interrelationships. ERD models are mainly used to build relational databases in terms of idea visualization and physical database architecture. The ERD is constructed with four main components: entity, relations, attributes and cardinality.

A definable thing or notion within a system, such as a person, object, concept, or event, is an ERD entity. An entity is represented as a rounded rectangle with its name on top and its properties listed in the entity shape's body. A relationship is nothing more but an association among two or more entities. An attribute is a property or characteristic of the entity that holds it. Lastly, cardinality defines the possible number of occurrences in one entity associated with the number of occurrences in another.

To develop an ERD model, first, entities must be identified. Secondly, the relationships and cardinality will be defined, and after identifying the attributes, it is possible to create an ERD (Figure 48).

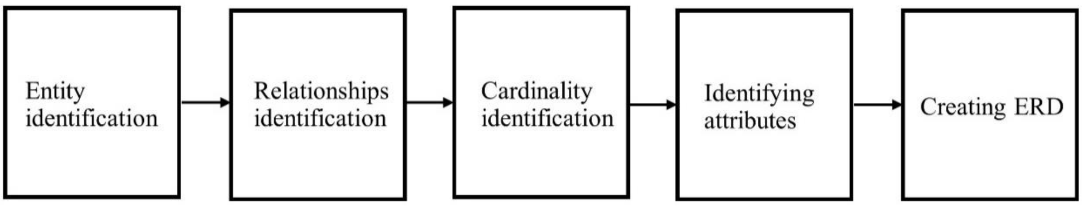
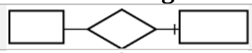
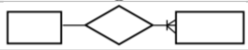
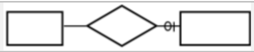
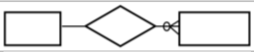
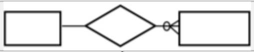
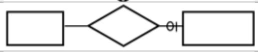
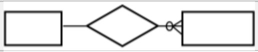
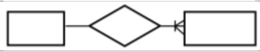
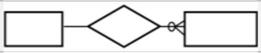
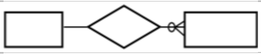
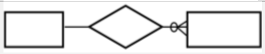
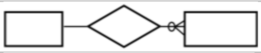
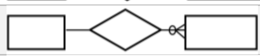
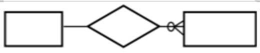
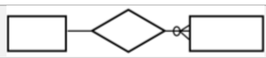
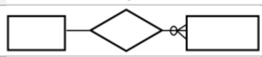
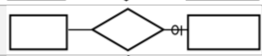
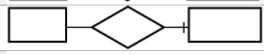
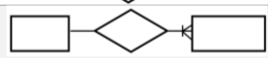



Figure 47: How to create an ERD (Author, 2022)

The database entities and attributes of each have been developed in the previous section. Each entity and its attributes are presented in separate tables in the relational database. In the next step, the relationships and cardinality of each entity must be developed. The cardinality relations present the possible number of occurrences in one entity which is associated with the number of occurrences in another. For example each users has a one-to-one cardinality with location as each user in office has a set placement. Table 21 presents the relationships between entities and the cardinality of each.

Table 21: Entities relationships and cardinality (Author,2022)

| Entity | Relationships with | Cardinality | Diagram |
|---|---|---|---|
| **User-Id** | User location | One-to-one |  |
| | Environmental Factors | One-to-many |  |
| | Façade prototypes | Many-to-one |  |
| | Comfort parameters | Many-to-many |  |
| | Users' adaptive controls | Many-to-many |  |
| | User-façade interaction | One-to-one |  |
| **User location** | User-Id | One-to-one |  |
| **Environmental Factors** | User-Id | Many-to-one |  |
| | Façade prototypes | Many-to-many |  |
| **Façade prototypes** | User-Id | One-to-many |  |
| | Environmental Factors | Many-to-many |  |
| | Façade adaptation | Many-to-many |  |
| **Comfort parameters** | User-Id | Many-to-many |  |
| | Façade adaptation | Many-to-many |  |
| | Users' adaptive controls | Many-to-many |  |
| **Façade adaptation** | Façade prototypes | Many-to-many |  |
| **Users' adaptive controls** | User-Id | Many-to-many |  |
| | Comfort parameters | Many-to-many |  |
| | User-façade interaction | Many-to-one |  |
| **User-façade interaction** | User-Id | One-to-one |  |
| | Users' adaptive controls | One-to-many |  |

By studying the relationship between the entities in Table 21 and understanding the cardinality, it is possible to draw the ERD model. For developing the ERD model, the Dbschema application has been used (Figure 49).

After Defining the ERD, the software specialists or IT specialists may receive the data from the architect and develop the physical model for the next step of the model's application.

## 6.3 Implementation

In the last phase of creating the proposed model, implementation of the model must be applied. As shown in Figure 34, this step is used after the software specialist developed the physical model. This phase will consist of three stages, testing the model, correcting the errors and updating the model.

The system developer must test the system before it is open for the users. All the errors and problems shown within the testing phase will be given as feedback. Thus, the model returns to the interface and web development stage to fix the errors.

The proposed model, designed as an active model, will be updated. Additional information can be added to the database during the time, according to the different research plans and as new needs require.

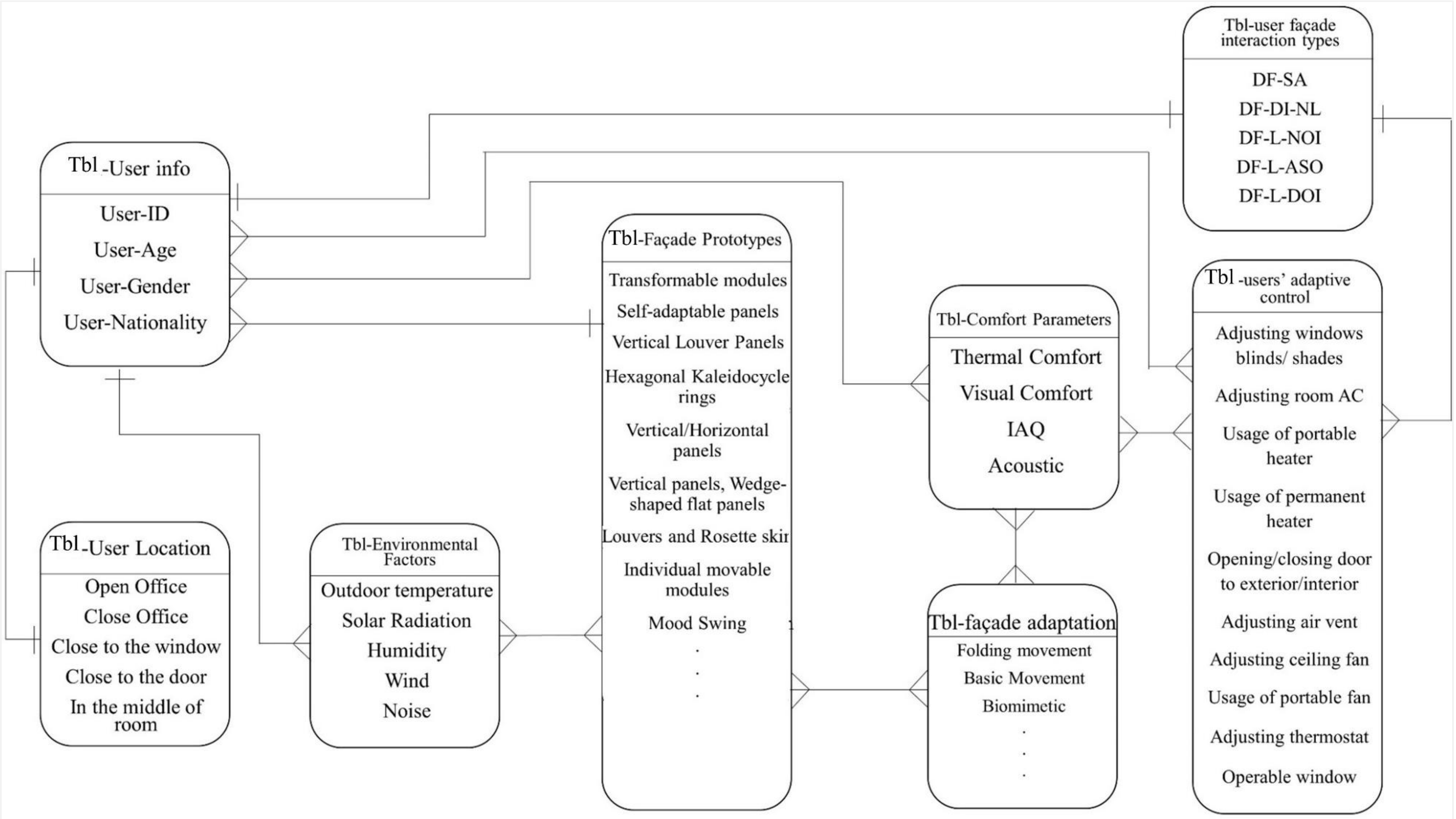



Figure 48: Entity Relation Diagram of the Dynamic Cloud-Based Model- (Tbl:Table) (Author, 2022)

## 6.4 Data Evaluation- Multi-criteria Analysis and Decision Making

In general, the proposed AI-powered dynamic cloud-based model has two primary goals: 1) determining the level of satisfaction and the precise moment of discomfort, and 2) carrying decision-making for CABS based on the occupants' perspective. The first result may be generated using the SPSS application. SPSS analyzes descriptive statistics, numerical result forecasts, and group identification data. Besides identifying the satisfaction level, the results of this section will be used in the matrix of criteria for decision-making. The model's second result will help the CABS' decision-making process. The following section will focus mainly on the data evaluation from the second data set (Figure 50).

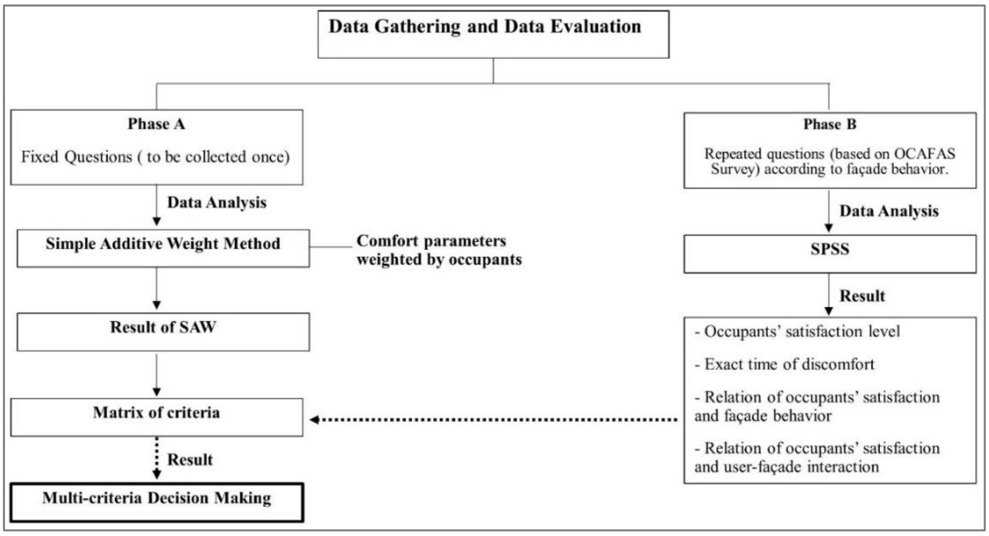



Figure 49: Data Gathering and Evaluation of the Model (Author, 2022)

Decision-making is a field of science concerned with defining various approaches, selecting the most appropriate scenario based on numerous aspects, and following the decision maker's expectations. Each choice is made in a unique context defined by the relevant evidence and its quality, the number of options, and the priorities at the moment of decision. When a decision is not evident and options clash, the multi-criteria analysis may make a quality conclusion. An additional benefit of multi-criteria research is the application's transparency. When dealing with many choices, multi-criteria analysis is a powerful method for handling difficult situations. The multi-criteria analysis will determine the optimum used CABS based on user comfort and satisfaction in this study. The decision-making process comprises three stages (Mateo, 2012). 1) definition of a problem, 2) weighting the criteria, 3) Ranking the alternative. The following parts will go through all three steps in detail.

### 6.4.1 Problem Identification

A selection for the most fitting technology based on occupants' demands, comfort, and satisfaction must be made from the wide variety of climate-adaptable building shell technologies provided in scientific publications, journals, and real-life examples. Understanding the CABS' technological advancements and functioning mechanisms may be accomplished through a literature review, as was done to some extent in the preceding chapters. However, understanding the occupants' demands and making appropriate decisions for this system is complex. As a result, criteria and how to conduct an evaluation to respond to this difficulty will be presented in this part.

To carry out a decision-making assessment on this system, the main domains of the research mentioned previously should be weighted in the second phase after describing the problem (in this case, occupants' comfort). The following section explains the Simple Additive Weight (SAW) method analysis, which aids in translating the occupants' feelings data to numerical data.

### 6.4.2 Weighting of Criteria- SAW Methodology

The established domains of the investigation will be weighted within section A of the proposed POE model. In this part, occupants will only answer one set of questions. The questions are graded on a scale of least to most effective. In this section, occupants will fundamentally organize the efficacy of comfort criteria on their satisfaction based on their feelings. Since this study is occupant-centric, comfort standards do not play a part in the decision-making process.

After obtaining these data from the occupants, the Simple Additive weighting methodology will be applied. The information gathered from the occupants will be converted to numerical data, allowing researchers to compare and make a decision. (Kaliszewski and Podkopaev, 2016).

SAW is one strategy for dealing with multi-criteria decision-making. The SAW method's main principle is calculating the mean of the weighted performance ratings for each alternative across all criteria. The SAW approach necessitates normalizing the choice matrix (X) to a scale that may be compared to all current alternative ratings. The following formula is used to calculate the weights of all criteria. (W, presenting the weight and C, presenting the criteria).

$$w = \frac{C1}{C1 + \cdots + Cn} x \; 100\%$$

SAW method evaluation may be studied with the criteria, and alternative ideas are dynamic. They can be adjusted for several scenarios, with the first step is setting the criteria (Bhandakkar and Chandure, 2015).

In the SAW technique, decision-makers choose weighting factors; in other words, policymakers must pick the weight preference in advance for each criterion; in this study, the analysis criteria weight is split into five possibilities provided by occupants. The resulting matrix will be formed once all the data have been calculated. Following that is the procedure of computing values. A higher number represents the better choice or the best decision using the Simple Additive Weighting approach.

When the weighing of criteria is complete, the equation may be arranged in a matrix containing criteria, weight, and alternatives. SAW provides a straightforward way to select suitable CABS technology. The approach allows researchers to view, evaluate, and judge the impact of each criterion and subcriterion on occupants at each step (Mateo, 2012).

### 6.4.3 Ranging the Alternatives

Many criteria will be studied to select the most suited CABS technology and user-façade interaction type to fulfil the occupants' demands. Each option will be evaluated using all the criteria and assigned a score based on SAW. The outcomes of varying the choices will be displayed in the chart-like figure. The chart will be the outcome of the multi-criteria analysis and will serve as the response to the research for decision-making based on occupant-centric principles (Mateo, 2012). (Kancane et al., 2015)

## 6.5 Chapter Summary

The purpose of this chapter was to present a novel POE model that could compete with the complexity and multi-ability of CABS. A dynamic cloud-based POE has been created by focusing on the occupant-centric study and understanding the fundamental ideas of prior studies in this sector. Within this chapter, all model components have been thoroughly discussed, and a conceptual model has been provided.

The suggested model addresses 1) facade behaviour, 2) types of user-facade interaction, and 3) occupants' feelings. In the presented approach, occupants are the focal point and serve as sensors; afterwards, to gather data, the sensors (occupants) are linked to the central cloud through a mobile app. All acquired data will be stored in the cloud, where it will be accessible at any time and from any location, and it can be shared with various study groups.

The information was gathered using a two-part mobile app survey. To weigh the comfort domains, occupants completed a single fixed study. Then the second half was replicated based on OCAFAS verified survey results for facade behaviour and design. Later, all acquired data will be analyzed in several phases, with the primary aims of 1) determining the level of satisfaction, 2) the precise timing of discomfort 3) multi-criteria analysis and decision-making from the standpoint of the occupants.

# Chapter 7

# CONCLUSION

Architecture is one of the most important professions for achieving sustainability in everyday life. Since the 1970s energy crisis, architects have paid particular attention to the subject of sustainability. Architects and scholars have been looking for new solutions and techniques to attain this aim ever since. In recent years, many solutions have been proposed due to technological advancements and developments in computer science. Climate Adaptive Building Shells are among the most promising options that have received much attention in recent years.

Because of its adaptability, flexibility, and multi-ability, CABS may respond to environmental and climatic changes throughout time, reducing the building's overall energy usage. As a result, CABS is a significant choice for improving building energy efficiency. According to the CABS literature review, most emphasis has been on the system's energy performance or technical operation. In chapter one, this assertion was supported by PRISMA analysis. As a result, the research's primary challenge, which focuses on the occupant-centric study of this subject, has been established. The analysis of the literature review highlights that the conventional evaluation methods cannot give accurate data about the system as they are not compatible with system's complexity. Usage of traditional questionnaires for a system which its properties change within time cannot highlight the correct time of discomfort. In this manner, the thesis has been formulated in following shapers to address mentioned limitations.

As a result, this thesis begins in chapter two by concentrating on one of the study's core keywords, "CABS." The description of CABS and the benefits and limitations have been discussed in Chapter 2—this chapter is mainly devoted to the CABS' database's current state and recent occupant-centric studies. Accordingly, 1) the CABS database (as of the most recent update in 2018) and 2) The types and contexts of user-facade interaction have been examined.

The intended conclusion of Chapter 2, presented as a three-phase analysis of CABS office buildings.  First, cases were classified based on climatic zones, as each climate region necessitates different design precautions. In the second phase, they were investigated by concentrating on user-façade interaction types (occupant-centric study). Finally, a new taxonomy for CABS office buildings was provided by considering many domains (typologies, control variables, and user-façade interaction types).

In general this chapter is focusing on finding answer for developed hypothesis one. The results presented in chapter 2 as new taxonomy of CABS according to user-façade interaction fills one of the literature gap of the field in regards to limited studies based on occupant-centric principles.

As described in chapters one and two, there is a lack of emphasis on occupant-centric CABS research. As a result, the system's user satisfaction and productivity levels are unclear. Traditionally, Post-Occupancy Evaluation (POE) has been employed to assess user satisfaction; consequently, chapter 3 focuses on POE as the second important keyword of the research. The main characteristics of POE have been explored in this chapter. And it emphasized that 1) the traditional and established POE approaches cannot meet the complexity of the CABS, necessitating the development of a unique POE model; and 2) the aim of POE for this study would be users and their comfort (thus, the comfort parameters need to be defined).

This chapter tries to highlight the hypothesis two of the thesis. By emphasising the POE variable needed for CABS evaluation, it become clear that there is a need for novel POE model compatible with complexity and adaptability of the CABS. In this manner a dynamic model must be proposed in this field of the study.

As highlighted in chapter 3, the element of evaluation in this thesis for defining a POE is occupants comfort parameters. Accordingly, in chapter four, the comfort characteristics and standards were investigated. It should be highlighted that this study focuses on occupants and their direct feelings toward the surrounding environment rather than the established comfort standards. However, to specify the study's comfort domains, it was necessary to review the comfort requirements once.

In the next step, to find answer for thesis's hypothesis three, a correlational study over CABS and POE has been presented. This study examined current advancements in CABS evaluations and recognised the need for an occupant-centric approach to gather and evaluate data continuously. The literature review identifies several issues associated with carrying POE for CABS. The literature synthesis demonstrates that existing established POE approaches are incapable of dealing with the complexities of CABS. Following the prior research, a few principles have emerged that future POEs for CABS should adhere to:

- Real-time Data gathering

- Real-time data evaluation
- considering user-façade interaction as a factor
- Defining the exact moment of dissatisfaction and discomfort
- feedback to the building operator.

As a result, this study proposes a dynamic POE model. The suggested AI-Powered cloud-based POE connects occupants directly to the cloud (as a concept of occupant-centric study) and collects data in real-time. In the model occupants will be used as the main sensors to detect the changes on shell and their feelings towards the changes. The model acts with a notification-based system to grasp the precise discomfort time based on façade behaviour and user-façade interaction. Thus, at the accurate time of the façade change, occupants may send comments on their feelings and satisfaction.

The model has been designed within three main stages of, conceptualization, application and implementation. Within the conceptualization all elements of the model and their relationship with each other have been identified, which as a result a conceptual model developed. In the second stage, the application of the model studied. In this stage the ML and database management system studied in detail. The study of physical analysis of the model makes it possible for architects to communicate with IT specialist to develop a physical model. All the entities and their relation must be developed by architect in the ERD model and later on according to what defined by architect IT specialist can develop a physical mode. Lasty in the implementation stage the role of software engineer and needed feedbacks has been explained.

The last section of the study has been dedicated to data evaluation methods and responding to the fourth hypothesis of this thesis. Two different strategies will be used to assess the stored data. The degree of satisfaction will be emphasised from one set of data with the help of the SPSS program. The optimum decision-making for CABS from the occupants' perspective will be carried out using the second set of data with the help of the Simple Additive Weight method and multi-criteria analysis. The proposed model may collaborate with the building management system and the building operator to enhance the living conditions of the occupants.

The suggested model fills several gaps in the POE evaluation of CABS; nevertheless, it is still in the conceptual stage, and further case studies are required. Future practical research can aid in identifying flaws in this model and advancing it accordingly. And, simultaneously, carrying experimental studies respond to the essential requirement for case studies, as there are relatively few case studies documented in this subject, particularly by focusing on occupants. The author intended to examine the model in practice as one of the study's primary purposes; however, due to the COVID-19 outbreak, lockdowns, and remote working, access to the offices and employees remained challenging. As a result, the investigation is completed by presenting the model in the conceptual format (Figure 50).

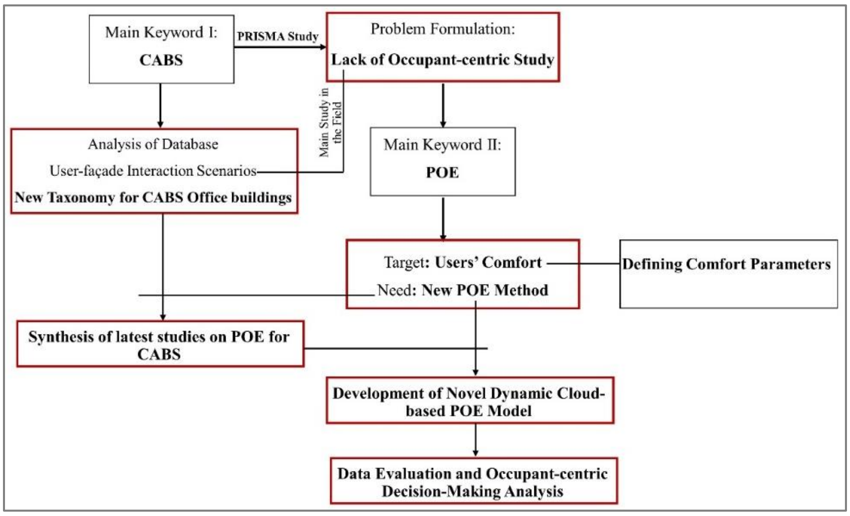


Figure 51: Summary of the Study's Main Results (Author, 2022)

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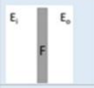
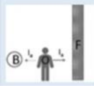
# APPENDICES

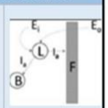
# Appendix A: CABS' Office Buildings Case Study

Table 22: CABS' office buildings analysis

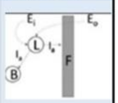
| # | Building name | Location | Climate zone | Façade highlight details | Building Information: Floor area | orientation | function | status | Detail description of the system: Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Yale Sculpture Building-2007 | New Haven Connecticut (USA) | Dfa | -Double Skin Facade<br>-Smart Envelope<br>-PV System<br>-Energy Saving | 5000 sq.m | All orientations | office | New built | Smart facade | -Thermal comfort<br>-Visual comfort<br>-Acoustic comfort<br>-Aesthetic quality | High-performance innovative materials and systems for absorbing and storing solar energy | TIM (Phase change) Blinds with slat angle control | Thermal (e.g. outdoor air temperature) | Mechanical<br>-Thermal |

| Control Operation Details: Control type | Response time | Degree of adaptively | Level of visibility | Economical Aspects: Economically viable? | Estimate the cost | Maintenance frequency | User-Facade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Intrinsic (auto reactive)<br>Extrinsic (requires external control) | Days seasons | Gradual | 01 Not visible (heat storage, phase change materials) | NO | High (double skin facades, high tech, etc) | Yearly | Scenario 1: Dynamic, Self-adjusting façade<br>Description: Adjustment is triggered by outdoor condition without need for logic<br><br>Scenario 2: Dynamic façade with direct interaction- no control logic<br>Description: the occupant operates the façade manually<br> |

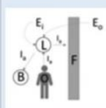
| # | Building name | Location | Climate zone | Façade highlight details | Building Information: Floor area | orientation | function | status | Detail description of the system: Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | OVAL COLOGNE OFFICES, -2010 | Cologne -DE | Cfb | -Automatic vertical shutter<br>-Day lighting regulation<br>-OVAL<br>-color in architecture | 43000 sq.m | All orientations | office | New built | Movable Facade | -Thermal comfort<br>-Visual comfort<br>-Aesthetic quality | Mobile screens for controlling solar radiation | Blinds with slat angle control | Mechanical (e.g. wind load) | Mechanical |

| Control Operation Details: Control type | Response time | Degree of adaptively | Level of visibility | Economical Aspects: Economically viable? | Estimate the cost | Maintenance frequency | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Intrinsic (auto reactive) | Seconds minutes | Gradual | 04 Visible, size or shape change (shutters, flaps, dynamic facade elements | NO | High (double skin facades, high tech, etc) | Monthly | Scenario: Logic with Environmental Sensing, no occupant interaction.<br>Description: the logic is informed from the sensing the outdoor conditions and control the façade accordingly.<br> |

| # | Building name | Location | Climate zone | Façade highlight details | Building Information: Floor area | orientation | function | status | Detail description of the system: Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | PALAZZO LOMBARDIA- 2010 | Milan- IT | Cfa | -Building Integrated Photovoltaic<br>-Skyscraper<br>-Renewable energy | 72000 sq.m | All orientations | office | New built | Smart facade | -Thermal comfort<br>-Energy generation | High-performance innovative materials and systems for absorbing and storing solar energy | -Screens / roller shades<br>-Blinds with slat angle control | -Thermal (e.g. outdoor air)<br>-Optical (e.g. daylight level, glare) | Mechanical |

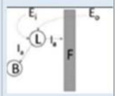
| Control Operation Details: Control type | Response time | Degree of adaptively | Level of visibility | Economical Aspects: Economically viable? | Estimate the cost | Maintenance frequency | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Intrinsic (auto reactive)<br>Extrinsic (requires external control) | Minutes | On/off | 02 Visible, no surface change (smart glazing) | NO | High (double skin facades, high tech, etc) | Monthly | Scenario: Logic with Environmental Sensing, no occupant interaction<br>Description: the logic is informed from the sensing the outdoor conditions and control the façade accordingly.<br> |

| # | Building name | Location | Climate zone | Façade highlight details | Building Information: Floor area | orientation | function | status | Detail description of the system: Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | ES VIAGENS BUILDING/ PT BUILDING, -1998 | Lisbon -PT | Csa | -Double skin facade; -automatic venetian blind and exhaust air-gap ventilation; -daylight regulation | 13250 sq.m | South East North west | office | New built | Intelligent façade | -Thermal comfort<br>-Visual comfort<br>-Acoustic comfort<br>-Aesthetic quality | Devices for managing natural ventilation in combination with mechanical ventilation systems | Blinds with slat angle control | Thermal (e.g. outdoor air temperature) Air quality (humidity, CO2 concentration, etc) | Mechanical |

| Control Operation Details: Control type | Response time | Degree of adaptively | Level of visibility | Economical Aspects: Economically viable? | Estimate the cost | Maintenance frequency | User-Facade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Extrinsic (requires external control) | Seconds | On/off | 03 Visible, surface change (lamellas, rollers, blinds) | YES | High (double skin facades, high tech, etc) | Yearly | Scenario: Dynamic façade, Logic with direct occupants' interaction<br>Description: the logic is informed from the sensing of indoor or outdoor conditions and control the façade accordingly. However, occupants can override the automation system for a time interval.<br> |

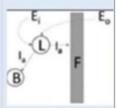
| # | Building name | Location | Climate zone | Façade highlight details | Building Information | | | | Detail description of the system | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Floor area | orientation | function | status | Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
| 5 | CAMPUS KOLDING, -2014 | Kolding -DK | Cfb | -shading device, -dynamic and adaptive envelope -energy saving | 5000 sq.m | South-East-West | office | New built | -Kinetic façade -Interactive façade -Responsive façade | -Thermal comfort Visual comfort Appearance (aesthetic quality) Personal users' control | Mobile screens for controlling solar radiation Building automation systems for the management of plants and elements of the building skin | -Aluminum -Shading with dual-axis tracking | Electromagnetic (e.g. solar radiation) ) | Mechanical |


| Control Operation Details | | | | Economical Aspects | | | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Control type | Response time | Degree of adaptively | Level of visibility | Economically viable? | Estimate the cost | Maintenance frequency | Scenario: Logic with Environmental Sensing, no occupant interaction. Description: the logic is informed from the sensing the outdoor conditions and control the façade accordingly |
| Intrinsic (auto reactive) Extrinsic (requires external control) | Second Minutes Hour | Gradual | 04 Visible, size or shape change (shutters, flaps, dynamic facade elements) | NO | High (double skin facades, high tech, etc) | Yearly | |



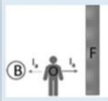
| # | Building name | Location | Climate zone | Façade highlight details | Building Information | | | | Detail description of the system | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Floor area | orientation | function | status | Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
| 6 | ALLIANZ HEADQUARTERS, -2014 | Wallisellen -CH | Dbf | - Curtain wall; shading; daylight control; thermal comfort; aesthetic quality | 40300 sq.m | All orientations | office | New built | Active Facade | -Thermal comfort -Visual comfort -Mass transfer control (e.g. condensation control) -Aesthetic quality - Personal users' control | -Mobile screens for controlling solar radiation -Building automation systems for the management of plants and elements of the building skin | Aluminum coated silver curtain | Thermal (e.g. outdoor air temperature) Optical (e.g. daylight level, glare) | Mechanical |


| Control Operation Details | | | | Economical Aspects | | | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Control type | Response time | Degree of adaptively | Level of visibility | Economically viable? | Estimate the cost | Maintenance frequency | Dynamic façade, logic with environmental sensing, no occupant's interaction. Description: the logic is informed from the sensing the outdoor conditions and control the façade accordingly. |
| Extrinsic (requires external control) | Seconds Minute | Gradual | 03 Visible, surface change (lamellas, rollers, blinds) | YES | High (double skin facades, high tech, etc) | Yearly | |



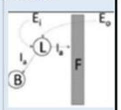
| # | Building name | Location | Climate zone | Façade highlight details | Building Information | | | | Detail description of the system | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Floor area | orientation | function | status | Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
| 7 | NORDIC EMBASSIES IN BERLIN, -1999 | Berlin -DE | Dfb | Pre-patinated lamellas; -copper -lamellas; -sun shade; -embassy; unified appearance | 179000 sq.m | All orientations | office | New built | Active Facade | -Thermal comfort -Visual comfort -Aesthetic quality | Mobile screens for controlling solar radiation | Copper -Blinds with slat angle control | Optical (e.g. daylight level, glare) | Mechanical |


| Control Operation Details | | | | Economical Aspects | | | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Control type | Response time | Degree of adaptively | Level of visibility | Economically viable? | Estimate the cost | Maintenance frequency | Dynamic façade with direct interaction- no control logic. Description: the occupant operates the façade manually or through the dedicated interaction. |
| Extrinsic (requires external control) | minutes | Gradual | 04 Visible, size or shape change (shutters, flaps, dynamic facade elements | YES | Low (traditional, residential, simple prefabricated, etc) | Monthly | |



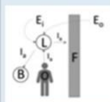
| # | Building name | Location | Climate zone | Façade highlight details | Building Information | | | | Detail description of the system | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Floor area | orientation | function | status | Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
| 8 | MEDIA-TIC -2007 | Barcelona -ES | BSk | Pneumatic facade and blind; daylight regulation; office building; ETFE | 23104 sq.m | South-East South-West | office | New built | Active Facade | -Thermal comfort -Visual comfort -Aesthetic quality | Building automation systems for the management of plants and elements of the building skin | ETFE -ETFE with serigrafy | Optical (e.g. daylight level, glare) | Pneumatical |


| Control Operation Details | | | | Economical Aspects | | | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Control type | Response time | Degree of adaptively | Level of visibility | Economically viable? | Estimate the cost | Maintenance frequency | Dynamic façade, logic with environmental sensing, no occupant's interaction. Description: the logic is informed from the sensing the outdoor conditions and control the façade accordingly. |
| Extrinsic (requires external control) | Minute | Gradual | 04 Visible, size or shape change (shutters, flaps, dynamic facade elements | specify): 20.791.486,00 € | High (double skin facades, high tech, etc) | Information not available | |



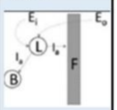
| # | Building name | Location | Climate zone | Façade highlight details | Building Information | | | | Detail description of the system | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Floor area | orientation | function | status | Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
| 9 | KFW WESTARKADE, 2010 | Frankfurt -DE | Cfb | Double facade; office building; low-energy building; ventilation flaps | 5000 sq.m | All orientations | office | New built | Advanced Facade | -Thermal comfort -Visual comfort Indoor air quality -Aesthetic quality | Technological solutions designed to increase and/or control comfort inside the building | Glass | Air quality (humidity, CO2 concentration, etc) | Mechanical |


| Control Operation Details | | | | Economical Aspects | | | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Control type | Response time | Degree of adaptively | Level of visibility | Economically viable? | Estimate the cost | Maintenance frequency | Scenario: Dynamic façade, Logic with direct occupants' interaction Description: the logic is informed from the sensing of indoor or outdoor conditions and control the façade accordingly. However, occupants can override the automation system for a time interval. |
| Extrinsic (requires external control) | minutes | On/off | 04 Visible, size or shape change (shutters, flaps, dynamic facade elements | NO | Information not available | Information not available | |



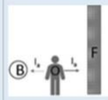
| # | Building name | Location | Climate zone | Façade highlight details | Building Information | | | | Detail description of the system | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Floor area | orientation | function | status | Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
| 10 | HEAD OFFICE OF AGC GLASS EUROPE, 2014 | Ottignies-Louvain-la-Neuve -DE | Cfb | Glass building; movable louvres; automated control; natural light | 10923 sq.m | All orientations | office | New built | Advanced façade Responsive facade | -Thermal comfort<br>-Visual comfort<br>Personal users' control<br>-Aesthetic quality | Mobile screens for controlling solar radiation<br>-Building automation systems for the management of plants and elements of the building skin | Glass<br>-Shading with dual-axis tracking | Optical (e.g. daylight level, glare) | Mechanical |


| Control Operation Details | | | | Economical Aspects | | | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Control type | Response time | Degree of adaptively | Level of visibility | Economically viable? | Estimate the cost | Maintenance frequency | |
| Intrinsic (auto reactive) | Second | On/off | 05 Visible, location or orientation change | NO | High (double skin facades, high tech, etc) | Monthly | Dynamic façade, logic with environmental sensing, no occupant's interaction. Description: the logic is informed from the sensing the outdoor conditions and control the façade accordingly. |



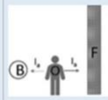

| # | Building name | Location | Climate zone | Façade highlight details | Building Information | | | | Detail description of the system | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Floor area | orientation | function | status | Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
| 11 | OFFICE BUILDING FRIEDRICH STRASSE 40, 2011 | Berlin -DE | Dfb | Rollers; high-performance facade; operable textile screens; double facade | 5000 sq.m | East | office | New built | Active Facade | -Thermal comfort<br>-Visual comfort<br>-Aesthetic quality | Mobile screens for controlling solar radiation | Glass Screens / roller shades Sliding-folding shutters | Optical (e.g. daylight level, glare) | Mechanical Manual |


| Control Operation Details | | | | Economical Aspects | | | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Control type | Response time | Degree of adaptively | Level of visibility | Economically viable? | Estimate the cost | Maintenance frequency | |
| Extrinsic (requires external control) | minutes | Gradual | 04 Visible, size or shape change (shutters, flaps, dynamic facade elements | NO | Information not available | Information not available | Dynamic façade with direct interaction- no control logic. Description: the occupant operates the façade manually or through the dedicated interaction. |




| # | Building name | Location | Climate zone | Façade highlight details | Building Information | | | | Detail description of the system | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Floor area | orientation | function | status | Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
| 12 | KUGGEN, 2011 | Goteborg SE | Dfd | -Double Skin Facade<br>-Smart Envelope<br>-PV System<br>-Energy Saving | 5350 sq.m | EAST | office | New built | Active façade | -Visual comfort<br>-Aesthetic quality | Mobile screens for controlling solar radiation | Rotating screen on circular railing | Optical (e.g. daylight level, glare) | Mechanical |


| Control Operation Details | | | | Economical Aspects | | | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Control type | Response time | Degree of adaptively | Level of visibility | Economically viable? | Estimate the cost | Maintenance frequency | |
| Extrinsic (requires external control) | Minute | Gradual | 05 Visible, location or orientation change | NO | Information not available | Information not available | Dynamic façade with direct interaction- no control logic. Description: the occupant operates the façade manually or through the dedicated interaction. |

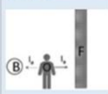



| # | Building name | Location | Climate zone | Façade highlight details | Building Information | | | | Detail description of the system | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Floor area | orientation | function | status | Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
| 13 | nZEB OFFICE BUILDING YMPÄRISTÖTALO, 2011 | Helsinki, -FI | Dfb | Nzeb; building integrated pv; double skin façade; solar shading | 6791 sq.m | South | office | New built | Active Façade | -Thermal comfort<br>- Energy generation | Technological solutions designed to increase and/or control comfort inside the building | Glass and PV<br>- PV panels have a shading function | Mechanical (e.g. wind load)<br>Thermal (e.g. outdoor air temperature) | Mechanical -Manual |


| Control Operation Details | | | | Economical Aspects | | | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Control type | Response time | Degree of adaptively | Level of visibility | Economically viable? | Estimate the cost | Maintenance frequency | |
| Intrinsic (auto reactive)<br>Extrinsic (requires external control) | minutes | Gradual | 02 Visible, no surface change (smart glazing) | YES | Information not available | Information not available | Dynamic façade with direct interaction- no control logic. Description: the occupant operates the façade manually or through the dedicated interaction. |

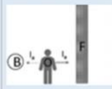

| # | Building name | Location | Climate zone | Façade highlight details | Building Information | | | | Detail description of the system | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Floor area | orientation | function | status | Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
| 14 | GSW HEADQUARTERS, 1999 | Berlin (DE), | Dfa | Double skin; solar chimney; natural lighting; louver system | 50000 sq.m | East-West | office | New built | Intelligent facade | -Thermal comfort<br>-Visual comfort<br>-Indoor air quality<br>-Aesthetic quality | Technological solutions designed to increase and/or control comfort inside the building | -Glass<br>-Blinds with slat angle control | Optical (e.g. daylight level, glare)<br>-Building heating/cooling load | Mechanical |


| Control Operation Details | | | | Economical Aspects | | | User-Facade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Control type | Response time | Degree of adaptively | Level of visibility | Economically viable? | Estimate the cost | Maintenance frequency | |
| Extrinsic (requires external control) | Minute | Gradual | 04 Visible, size or shape change (shutters, flaps, dynamic facade elements | NO | Information not available | Information not available | Dynamic façade with direct interaction- no control logic. Description: the occupant operates the façade manually or through the dedicated interaction. |



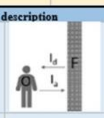
| # | Building name | Location | Climate zone | Façade highlight details | Floor area | orientation | function | status | Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **Building Information** | | | | **Detail description of the system** | | | | | |
| 15 | INFORMATION COMMUNICATION TECHNOLOGY CENTRE, 2003 | Lucca (IT), | Csa | Smart facade; pv; double skin facade | 5000 sq.m | South, East | office | New built | Smart facade | -Thermal comfort<br>-Visual comfort<br>-Acoustic comfort<br>-Aesthetic quality<br>-Energy generation | Technological solutions designed to increase and/or control comfort inside the building | PV<br>-Glass<br>-Screens / roller shades | Optical (e.g. daylight level, glare) | Mechanical |

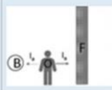
| Control type | Response time | Degree of adaptively | Level of visibility | Economically viable? | Estimate the cost | Maintenance frequency | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| **Control Operation Details** | | | | **Economical Aspects** | | | |
| Extrinsic (requires external control) | Minute | Gradual | 03 Visible, surface change (lamellas, rollers, blinds) | YES | Medium (curtain walls, ventilated facades, etc) | Yearly | Dynamic façade with direct interaction- no control logic.<br>Description: the occupant operates the façade manually or through the dedicated interaction. |




| # | Building name | Location | Climate zone | Façade highlight details | Floor area | orientation | function | status | Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **Building Information** | | | | **Detail description of the system** | | | | | |
| 16 | KIEFER TECHNIC SHOWROOM,2007 | BAD GLEICHENBERG (A), | Dfb | Kinetic facade; double skin facade; shading device | 298 sq.m | South | office | New built | Kinetic façade | -Thermal comfort<br>-Visual comfort<br>Personal users' control<br>-Aesthetic quality | Mobile screens for controlling solar radiation | Aluminum<br>-Blinds with slat angle control | Optical (e.g. daylight level, glare) | Mechanical |

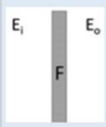
| Control type | Response time | Degree of adaptively | Level of visibility | Economically viable? | Estimate the cost | Maintenance frequency | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| **Control Operation Details** | | | | **Economical Aspects** | | | Dynamic façade with direct interaction- no control logic<br>Explanation: the occupants commands the façade to display information and receives information from it. |
| Extrinsic (requires external control) | Seconds | Gradual | 03 Visible, surface change (lamellas, rollers, blinds) | NO | Medium (curtain walls, ventilated facades, etc.) | Yearly | Dynamic façade with direct interaction- no control logic.<br>Description: the occupant operates the façade manually or through the dedicated interaction. |



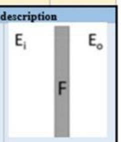

| # | Building name | Location | Climate zone | Façade highlight details | Floor area | orientation | function | status | Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **Building Information** | | | | **Detail description of the system** | | | | | |
| 17 | TELEFONICA HEADQUARTERS, 2008 | MADRID-ES | Csb | Glass facade; double skin facade; shading device | 5000 sq.m | All orientations | office | New built | Smart facade | -Thermal comfort<br>-Visual comfort<br>-Acoustic comfort<br>-Aesthetic quality | Technological solutions designed to increase and/or control comfort inside the building | Glass | Optical (e.g. daylight level, glare) | |

| Control type | Response time | Degree of adaptively | Level of visibility | Economically viable? | Estimate the cost | Maintenance frequency | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| **Control Operation Details** | | | | **Economical Aspects** | | | |
| Intrinsic (auto reactive) | | | 01 Not visible (heat storage, phase change materials) | NO | Information not available | Yearly | Scenario: Dynamic, Self-adjusting façade<br>Description: Adjustment is triggered by outdoor condition without need for logic |



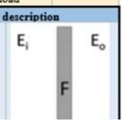

| # | Building name | Location | Climate zone | Façade highlight details | Floor area | orientation | function | status | Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **Building Information** | | | | **Detail description of the system** | | | | | |
| 18 | SOLAR XXI – BIPV/T SYSTEMS, -2006 | LISBON (PT), | Csa | -Automatic vertical shutter<br>-Day lighting regulation<br>-OVAL<br>-color in architecture | 1500 sq.m | South | office | New built | Smart Façade | -Thermal comfort<br>-Visual comfort<br>-Acoustic comfort<br>-Energy management (harvesting, storing, supply)<br>-Indoor air quality<br>-Energy generation<br>-Aesthetic quality | Technological solutions designed to increase and/or control comfort inside the building | PV<br>PCM | Building heating/cooling load | Thermal |

| Control type | Response time | Degree of adaptively | Level of visibility | Economically viable? | Estimate the cost | Maintenance frequency | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| **Control Operation Details** | | | | **Economical Aspects** | | | |
| Extrinsic (requires external control) | Hours Seasons | On/off | 01 Not visible (heat storage, phase change materials) | NO | High (double skin facades, high tech, etc) | Yearly | Scenario: Dynamic, Self-adjusting façade<br>Description: Adjustment is triggered by outdoor condition without need for logic |



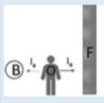

| # | Building name | Location | Climate zone | Façade highlight details | Floor area | orientation | function | status | Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **Building Information** | | | | **Detail description of the system** | | | | | |
| 19 | ENERGYbase, 2008 | VIENNA -AT | Dvb | Passive house standard; double skin facade; shading device; stepped facade | 9200 sq.m | South | office | New built | Active facade | -Thermal comfort<br>-Visual comfort<br>-Acoustic comfort<br>-Aesthetic quality<br>-Indoor air quality<br>-Energy generation | Technological solutions designed to increase and/or control comfort inside the building | Glass and PV<br>-Screens / roller shades | Optical (e.g. daylight level, glare)<br>-Building heating/cooling load | -Thermal<br>-Chemical |

| Control type | Response time | Degree of adaptively | Level of visibility | Economically viable? | Estimate the cost | Maintenance frequency | User-Façade Interaction type and description |
|---|---|---|---|---|---|---|---|
| **Control Operation Details** | | | | **Economical Aspects** | | | |
| Intrinsic (auto reactive) | Minute | On/off | 01 Not visible (heat storage, phase change materials) | NO | Information not available | Yearly | Scenario: Dynamic, Self-adjusting façade<br>Description: Adjustment is triggered by outdoor condition without need for logic |

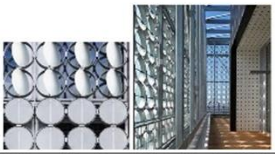


| # | Building name | Location | Climate zone | Façade highlight details | Building Information: Floor area | orientation | function | status | Detail description of the system: Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | FIRE AND POLICE STATION, -2004 | BERLIN -DE | Dfb | Fire station; double skin facade; shading device; glass shingles | 6900 sq.m | West | office | New built | Kinetic façade | -Thermal comfort<br>-Visual comfort<br>-Acoustic comfort<br>-Aesthetic quality | Mobile screens for controlling solar radiation | Glass<br>-Blinds with slat angle control | Optical (e.g. daylight level, glare) | Mechanical |

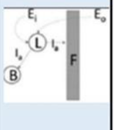
| Control Operation Details: Control type | Response time | Degree of adaptively | Level of visibility | Economical Aspects: Economically viable? | Estimate the cost | Maintenance frequency | User-Facade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Extrinsic (requires external control) | Minute | On/off | 03 Visible, surface change (lamellas, rollers, blinds) | NO | Information not available | Monthly | Dynamic façade with direct interaction- no control logic.<br>Description: the occupant operates the façade manually or through the dedicated interaction. |




| # | Building name | Location | Climate zone | Façade highlight details | Building Information: Floor area | orientation | function | status | Detail description of the system: Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 21 | RMIT DESIGN HUB, 2012 | MELBOURNE (AUS), | Cfc | Office building; sunscreen; bipv; evaporative cooling | 13000 sq.m | All orientations | office | New built | Responsive facade | -Thermal comfort<br>-Visual comfort<br>-Indoor air quality<br>-Energy generation<br>-Aesthetic quality | Building automation systems for the management of plants and elements of the building skin | BIPV, glass disks | Optical (e.g. daylight level, glare) | Mechanical |

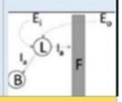


| Control Operation Details: Control type | Response time | Degree of adaptively | Level of visibility | Economical Aspects: Economically viable? | Estimate the cost | Maintenance frequency | User-Facade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Extrinsic (requires external control) | Minute | Gradual | 03 Visible, surface change (lamellas, rollers, blinds) | NO | Information not available | Yearly | Dynamic façade, logic with environmental sensing, no occupant's interaction.<br>Description: the logic is informed from the sensing the outdoor conditions and control the façade accordingly. |



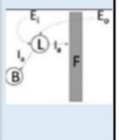

| # | Building name | Location | Climate zone | Façade highlight details | Building Information: Floor area | orientation | function | status | Detail description of the system: Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 22 | AGBAR TOWER BARCELONA 2004 | BARCELONA -ES | Cfc | Double-skin façade; glass louvres; tower | 30000 sq.m | All orientations | Office and conference centre | New built | Active façade | -Thermal comfort<br>-Visual comfort<br>-Energy generation<br>-Aesthetic quality | Mobile screens for controlling solar radiation<br>-Building automation systems for the management of the building skin | Glass<br>-Blinds with slat angle control | Thermal (e.g. outdoor air temperature)<br>Optical (e.g. daylight level, glare) | Mechanical |

| Control Operation Details: Control type | Response time | Degree of adaptively | Level of visibility | Economical Aspects: Economically viable? | Estimate the cost | Maintenance frequency | User-Facade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Intrinsic (auto reactive) | Minute | Gradual | 03 Visible, surface change) | NO | Information not available | Yearly | Dynamic façade, logic with environmental sensing, no occupant's interaction.<br>Description: the logic is informed from the sensing the outdoor conditions and control the façade |



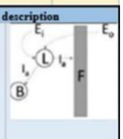

| # | Building name | Location | Climate zone | Façade highlight details | Building Information: Floor area | orientation | function | status | Detail description of the system: Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 23 | AL BAHAR TOWERS, 2012 | ABU DHABI (AE), | Bhv | MASHRABIYA; DOUBLE SKIN FACADE; SHADING DEVICE; PTFE | 5600 sq.m | South, East, West | office | New built | Responsive façade | -Thermal comfort<br>-Visual comfort<br>-Acoustic comfort<br>-Aesthetic quality | Mobile screens for controlling solar radiation<br>Building automation systems for the management of plants and elements of the building skin | PTFE<br>-triangulate units | Optical (e.g. daylight level, glare) | Mechanical |

| Control Operation Details: Control type | Response time | Degree of adaptively | Level of visibility | Economical Aspects: Economically viable? | Estimate the cost | Maintenance frequency | User-Facade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Intrinsic (auto reactive) | minutes | Gradual | 04 Visible, size or shape change (shutters, flaps, dynamic facade elements | NO | Information not available | Yearly | Dynamic façade, logic with environmental sensing, no occupant's interaction.<br>Description: the logic is informed from the sensing the outdoor conditions and control the façade accordingly. |




| # | Building name | Location | Climate zone | Façade highlight details | Building Information: Floor area | orientation | function | status | Detail description of the system: Façade system type | purpose | Technological features | Material and shading types | Trigger type | Actuator type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24 | THYSSENKRUPP QUARTER, 2010 | Essen (DE), | Cfb | Double skin facade, smart envelope, steel sheets, energy saving | 25000 sq.m | South, East, West | office | New built | Kinetic facade | -Thermal comfort<br>-Visual comfort<br>-Acoustic comfort<br>-Aesthetic quality | Mobile screens for controlling solar radiation<br>-Building automation systems for the management of plants and elements of the building skin | Steel<br>-Blinds with slat angle control | Thermal (e.g. outdoor air temperature) | Mechanical |

| Control Operation Details: Control type | Response time | Degree of adaptively | Level of visibility | Economical Aspects: Economically viable? | Estimate the cost | Maintenance frequency | User-Facade Interaction type and description |
|---|---|---|---|---|---|---|---|
| Intrinsic (auto reactive) | Minute | Gradual | 03 Visible, surface change (lamellas, rollers, blinds) | NO | High (double skin facades, high tech, etc) | Yearly | Dynamic façade, logic with environmental sensing, no occupant's interaction.<br>Description: the logic is informed from the sensing the outdoor conditions and control the façade accordingly. |



## Appendix B: The Initial Sample of Survey (Two Phases of Data Collection)

**Section A:**

- Please give weights to the following domains (1 to 5) based the 5 the most effective and 1 the least effective domain on the satisfaction level.

| View | Visual comfort (glare, illuminance level | Thermal comfort | Adaptation control | Acoustic comfort |
|---|---|---|---|---|

- Please give weights to the following domains (1 to 5) based the 5 the most effective and 1 the least effective domain on the productivity level.

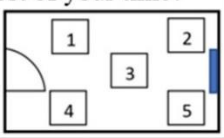
| View | Visual comfort (glare, illuminance level | Thermal comfort | Adaptation control | Acoustic comfort |
|---|---|---|---|---|

- Please give weights to the following domains (1 to 5) based the 5 the most effective and 1 the least effective domain on the disturbance during day.
-

| View | Visual comfort (glare, illuminance level | Thermal comfort | Adaptation control | Acoustic comfort |
|---|---|---|---|---|

**Section B:**

**A- PERSONAL DATA**

| | | | | | |
|---|---|---|---|---|---|
| **A1:** Gender | Man | Woman | | | |
| **A2:** Age | | | | | |
| **A3:** How long have you been working here? | | | | | |
| **A4:** Are you near a window (within 4 m)? | YES | NO | | | |
| **A5:** Are you near an exterior wall (within 4 m)? | YES | NO | | | |
| **A6:** What best describes the area of building where your space is located? | North | East | South | West | Core |
| | Don't know | | | | |
| **A7:** On which floor of the building is your space located? | 1rst | 2nd | 3rd | Other: | |
| **A8:** In which place do you spend most of your time?   | 1 | 2 | 3 | 4 | 5 |

**A- INTERACTION WITH FAÇADE:**

| | | | | | |
|---|---|---|---|---|---|
| **B1**: Are you satisfied with the facade? | 1=not at all | 2 | 3 | 4 | 5=Extremely Good |
| **B2:** Which of the following do you personally adjust or control in your space? | Window blinds or shades | Room AC unit | Portable heater | Permanent heater | Door to interior space |
| | Door to exterior space | Adjustable air vent in wall or ceiling | Ceiling fan | Ajustable floor/air vent (diffuser) | Portable fan |
| | Thermostat | Operable window | None of these | Other: | |
| **B3**: what do you rate your level of interaction with facade | 1=not at all | 2 | 3 | 4 | 5= complete control |
| **B4:** Are you satisfied with the interaction you have with the facade? | 1=not at all | 2 | 3 | 4 | 5= complete control |

**B- ADAPTATION CONTROL**

| | | | | | |
|---|---|---|---|---|---|
| **C1**: How much is your knowledge about the working mechanism of the façade? | 1=not at all | 2 | 3 | 4 | 5=Extremely Good |
| **C2:** How much is the impact of the adaptation control level on your general satisfaction level? | 1 | 2 | 3 | 4 | 5 |
| **C3**: what do you rate the disturbance level due to lack of adaptation control? | 1 | 2 | 3 | 4 | 5 |

**C- GENERAL FEELINGS:**

| **View and Visual comfort** | | | | | |
|---|---|---|---|---|---|
| **Q1:** How often are you disturbed by glare (direct sunlight, bright sky, or bright walls) | 1 | 2 | 3 | 4 | 5 |
| **Q2:** How do you judge the current illuminance level on the work plane? | 1 | 2 | 3 | 4 | 5 |
| **Q3:** How comfortable is the current illuminance level on the work plane? | 1 | 2 | 3 | 4 | 5 |
| **Q4**: Do you think the facade management system adapt enough to meet your needs? | 1 | 2 | 3 | 4 | 5 |
| **Q5:** Does the change of brightness and view due to the movement of the facade disturb you? | 1 | 2 | 3 | 4 | 5 |
| **Thermal comfort** | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| **Q6:** How do you rate your immediate thermal sensation: | Cold | Slightly cool | Neutral | Slightly warm | Hot |
| **Q7:** How do you perceive this temperature | 1=not at all | 2 | 3 | 4 | 5=Extre mely |
| **Q8:** Are you satisfied with the temperature in general? | 1 | 2 | 3 | 4 | 5 |
| **Q9:** Does the thermal adaptation change of facade disturb you? | | | | | |
| **Acoustic comfort** | | | | | |
| **Q10:** The noise associated with the movement of facade disturb you: | 1=not at all | 2 | 3 | 4 | 5=Extre mely |
| **Q11:** The noise associated with working in an open office disturb you: | 1 | 2 | 3 | 4 | 5 |

Please add any comment related to façade adaptation and your general satisfaction and productivity level: